

DYNAMICS OF WATER AND NITROGEN STRESSES ON CORN
GROWTH, YIELD, AND NUTRIENT UPTAKE

By

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Florida corn production on irrigated sandy soils, under variable and unpredictable rainfall conditions, requires the support of a management system capable of predicting water and/or nitrogen stresses during plant growth. Additional research to improve understanding, measurement, and prediction of water and nitrogen stresses is needed.

To meet this need, a split-plot field experiment having corn (Zea mays L.) as test crop and irrigation-nitrogen combinations as treatments was conducted on Millhopper fine sand, a loamy, hyperthermic, Grossarenic Paleudult soil. Periodic water and nitrogen stresses were imposed by proper irrigation-nitrogen combinations. Plant samples were taken throughout the growing season, at two weeks intervals.

Plant nitrogen, phosphorus, and potassium content, as a function of time and plant component, showed significant water and nitrogen effects. Larger nutrient content differences occurred during late vegetative and early reproductive growth stages. Grain yield, dry matter yield, and nitrogen, phosphorus, and potassium uptake were significantly affected by stresses. Dry matter yield, cumulative nitrogen, and cumulative potassium uptake were adequately described by the cumulative Weibull distribution function, which was used to compute the respective rates. Cumulative phosphorus uptake was described by a parabolic equation. Quantitative measures of water and nitrogen stress as percent decrease in absolute growth rates agreed with visual plant symptoms. Measured cumulative nitrogen uptake by corn agreed with nitrogen uptake predicted by the NITROSIM simulation model.

The results from this study indicated that the joint management of water and nitrogen is decisive to avoid yield reductions due to periodic water and nitrogen stress. Stresses of either water or nitrogen can be adequately quantified using crop growth rates.

The existing simulation model can and should be used for research planning and holds promise for future computer-aided water and nitrogen management.

CHAPTER 1 INTRODUCTION

Corn (Zea mays L.) grain yields on coarse-textured soils have been shown to be inconsistent over the years. Recent and current research has shown that (1) yields on sandy soils are not consistent in relation to applied N fertilizers and that, (2) under irrigation, excessive leaching of mobile plant nutrients (nitrate-N and K) may occur, which in turn may reduce yields.

In the last decade, irrigated acreage has increased by more than 60 % in the Southeastern United States. Since 1968, over one-half million hectares of sandy soils in Nebraska have been brought under irrigation. These rather rapid expansions in irrigated agriculture on sandy soils are attributed to the development of center-pivot sprinkler irrigation systems (Cochran et al., 1983; and Watts and Martin, 1981).

The intensification of agriculture on coarse-textured soils has required increased application of N fertilizer in order to achieve economic levels of production. Development is continuing and most of the sprinkler-irrigated land is being used for corn production (Watts and Martin, 1981; Hammond et al., 1981; Rhoads, 1981; Robertson et al., 1981; and Rhoads et al., 1978).

In Florida the combination of variable rainfall distribution and low water and nutrient holding capacities of the well-drained sandy soils makes crops in this region subject to water and nutrient stresses at various times throughout the growing season.

During the last four years the frequency and/or duration of dry periods were such that they drove many nonirrigated corn-growers to search for alternative crops. Irrigation is being used during relatively short but frequent droughts to supplement the rainfall. Frequency and amounts of irrigation water can be controlled to conform to a given soil storage capacity and crop rooting depth, while rainfall can be neither controlled nor predicted with certainty. Being unpredictable, rainfall can occur at such times and in amounts so as to cause the downward displacement of residing soil water and soluble nutrients to soil depths below the root zone. Therefore, under conditions of no plant water stress, water inputs may be excessive enough to cause the downward transport of nutrients such as K and N. As a consequence, yields may not reach potential levels due to nutrient stress.

Studies have been conducted on irrigation scheduling to minimize seepage losses of irrigation and rainfall water in deep well-drained sandy soils of Florida (Hammond et al., 1967, 1981; Robertson et al., 1973, 1981; Rhoads and Stanley, 1973, 1975a, 1975b; Stanley and Rhoads, 1971). Few studies have addressed the coupling between water and N inputs (Graetz et al., 1973; Rhoads et al., 1978; and Rhoads and Stanley, 1981).

Past and current research, including modeling efforts, have indicated that additional studies on the response of corn plants to the availability of water and N, as a function of time, were needed. Contributing to this need, the present study was conducted to measure and analyze the effects of periodic water

and N stresses on dynamics of corn growth, yields, and nutrient uptake. Within this major objective, the study attempted to

- (a) measure and analyze the cumulative plant N, P, and K uptake as a function of time, and as influenced by water and N stresses,
- (b) relate quantitative measures of stress based on crop growth rates with plant yield,
- (c) compare measured cumulative plant N uptake with predictions of an existing simulation model (NITROSIM).

CHAPTER 2 LITERATURE REVIEW

Corn Development and Water Stress

In the last 10 years, average corn yields in Florida have varied from 2500 to 3750 kg/ha. This variation has been attributed almost exclusively to variation in rainfall within the corn growth period, for either early or late planted corn (USDA, 1982). Results from nonirrigated corn experiments conducted under natural rainfall conditions have been so variable that they are often inconclusive (Robertson et al., 1981). On well drained sandy soils it has been shown that a growing crop can develop water stress within 3 days following a "good" rainfall or irrigation. Grain yields as low as 500 kg/ha, with no irrigation, and over 12500 kg/ha, with irrigation, have been reported (Hammond et al., 1981; Rhoads, 1981).

Plant organs influenced by water stress were shown to depend largely on the timing of stress in relation to plant differentiation and growth. In general, a plant organ is most sensitive to stress during periods of rapid growth (Begg and Turner, 1976). Using various techniques, combined with a controlled environment, Archer et al. (1982) were able to produce the following detailed scheme for differentiation in corn. Leaf differentiation ends at 7-8 days after plant emergence. Tassel differentiation started after leaf differentiation ended. Shortly after the beginning of tassel-branch differentiation,

tassel florests were initiated and were laid down over a period of 7-10 days. At the same time while leaf differentiation was occurring, the ear shoot was also being initiated. An ear shoot, which will subsequently develop into a cob, is differentiated in the axil of each leaf and this process progresses until the primary ear is differentiated. The number of nodes, and therefore the number of potential ears, is a function of the genotype as modified by temperature and photoperiod. Following differentiation of the uppermost or primary ear, apical dominance tends to depress the development of ears carried in more basal positions. After the initial phase of differentiation, a second phase begins around 23 days after plant emergence in the growth room, when ovules were initiated in the developing ears. Ovule differentiation lasted for 7-10 days with approximately one day between successive rows of ovules around the cob. Tassel sex expression was determined around the same time as ovules were developing in the ears. Microspore meiosis occurred 37 days after plant emergence.

As the scheme of corn differentiation shows, the major reproductive structures and the number of kernels, which can later develop to produce grain, are all determined at an early period in the corn life cycle. A rapid progression through these early stages, as caused by water or nutrient stress, may result in a subsequent yield decrease because of a decrease in the number of morphological components initiated.

Studies of the effect of stresses during corn seedling age on subsequent growth or grain yield are rare. Working with

nine-day-old corn plants, for periods of 6 days, Barlow et al. (1976) found that decreasing the leaf water potential resulted in decreases in rate of leaf elongation and total dry matter accumulation while the soluble carbohydrate concentration increased. The restriction of leaf elongation caused by water stress seems to be of particular importance when the crop is in the seedling stage, or early vegetative stage, when the plant canopy is not closed. In this situation, the rate of increase in photosynthetic area, or the leaf area index, is a major determinant of the crop growth rate.

Irreversible damage can be caused by plant water deficits, and such damage at any particular stage may affect subsequent growth rate and total yield at maturity (Vaadia et al., 1961). In a study reported by Denmead and Shaw (1960), corn plants subjected to moisture stress (soil moisture content depleted to wilting point) in the vegetative stage (30 days after planting to the commencement of visible tasseling) were shorter, though statistically not significantly different, than those not subjected to stress and showed a decrease of the ear leaf area. Grain yield was reduced by 25 %.

Studying corn water relations in Zimbabwe, Wilson (1968) found that drought about three weeks before flowering depressed yield by about 15 % and that this depression resulted from a 20 % reduction in grain number.

The concept that crops are more sensitive to water deficits at particular stages of growth has been widely accepted in the

literature. There are indications that it may be due to a different degree of stress rather than sensitivity at a particular stage.

During flowering and the formation of fruit, root growth is retarded or has ceased completely, and the rate of water absorption by plants becomes increasingly dependent on the flow of water through the soil to root surface. Thus, under unsaturated soil-water conditions in the presence of high evaporative demand, severe water stress can occur during the rapid growth of reproductive organs (Begg and Turner, 1976; and Waldren, 1983). Studying the effects of moisture stress at specific growth stages of corn, Robins and Domingo (1953) found that soil moisture depression to the wilting percentage for periods of one to two days, during tasseling or pollination, resulted in as much as 22 % grain yield reduction. Periods of six to eight days gave a yield reduction of about 50 %. Denmead and Shaw (1960) found that water stress applied at the silking stage (from commencement of tasseling to 5 days after plants were 75 % silked) caused a 50 % reduction in grain yield. Under tropical conditions, Wilson (1968) reported a 25 % reduction in final corn grain yield by applying the water stress (irrigation withheld until soil matric potential had fallen below -15 atmospheres for eight days) during the silking stage. The most marked depression (49 %) in final yield resulted from drought some three weeks after flowering in a growing season of 152 days (complete leaf senescence).

As a factor in reducing plant growth under moisture stress, the reduced translocation of carbohydrates is rarely mentioned. According to Brevedan and Hodges (1973), this should not occur because the pressure flow hypothesis would require a pressure potential gradient between leaves and the receiving organs before any translocation of sugars could occur. Such pressure potential gradient would be reduced as the internal moisture deficit increased. If this hypothesis is correct, translocation could be one of the chief physiological factors limiting growth under unfavorable moisture conditions.

Water use efficiency of field crops has increased considerably over the past fifty years, but it has been achieved largely through increasing crop yields rather than through any appreciable conservation of water use. The literature indicates that most of the negative effects of water stress on carbon gain is caused by closure of stomata, increasing stomata resistance. Under this condition, no improvement of the water use efficiency has been shown for corn.

Therefore, adequate water management for corn should be to minimize the development of moisture stress and avoid increased stomatal resistance (Sinclair et al., 1975; Kluge, 1976; and Begg and Turner, 1976).

Corn Development and N Stress

Nitrogen stress can occur either by insufficient inputs or leaching of applied N beyond the root zone. Under nonirrigated agriculture, samples taken under different management systems, in

some cases compared to adjacent native pastures, have indicated only slight movement of N. Under irrigated systems, N may be leached beyond the root zone (Muir et al., 1976; Graetz et al., 1973; Watts and Martin, 1981; Lembke and Thorne, 1980; Gerwing et al., 1979; and Balasubramanian et al., 1973).

On well-drained sandy soils, drainage from irrigation and/or rainfall may be sufficient to remove essentially all of the nitrate not utilized by the plant-root system. In addition, nitrification is sufficiently rapid to convert most of the ammonium added into nitrate during the crop growth period, which leads to an increased potential for leaching losses. Also, under high leaching conditions most of the available N may be moved below a young crop's root zone. Hence, uptake of N may be delayed until the roots grow to the soil depth zone containing the N supply. If enough leaching takes place early in the growing season, the bulk of the nitrate may move to the lower part of the root zone, where the plant may be unable to obtain a sufficient amount to meet its demand (Graetz et al., 1973; Long and Huck, 1980; and Watts and Martin, 1981). Frequent irrigation and split applications of fertilizer N have been tested in order to maximize grain yields and at the same time minimize water seepage and N leaching losses (Hammond et al., 1981; Rhoads and Stanley, 1981; Rhoads, 1981; and Rhoads et al., 1978).

Many reports have shown the effects of plant uptake on water and N losses from the root zone, but few have reported on the time of application of N inputs on plant development and yield (Terry and McCants, 1970; Muir et al., 1976; Gerwing et al.

1979; and Long and Huck, 1980). Using a sandy soil with low indigenous N, Schreiber et al. (1962) showed that kernel rows per ear in a hybrid corn can be affected by N during the first 7 weeks after planting. Row numbers increased if as little as 28 kg/ha of N was added at planting. Row numbers appeared to be unaffected by the irrigation levels used and were increased by N only in the early stage of growth. No effects on final yield were detected. Jung et al. (1972), having N as a limiting factor, found a distinct reduction in corn grain yield for plants receiving N after the 8th week (after planting). They interpreted it as an indication of a stage of development beyond which the corn plant was unable to efficiently assimilate the available N into its growth process. Russelle et al. (1983) showed that once the corn crop has entered the rapid growth phase, the time of maximum N accumulation is dependent primarily on available N supply in the soil. Grain yield was reduced by early deprivation only when N uptake ceased during the early grain filling period.

Under no water stress, much of the year-to-year variation in plant response to inorganic N fertilizer has been attributed to the movement of nitrate or, equivalently, to N stress (Burns, 1974; Rhoads et al., 1978; and Robertson et al., 1981). Data from Lembke and Thorne (1980) show that for the 1974-76 period, with rainfalls plus irrigations of 116.5 cm, 96.5 cm, and 82.7 cm, corn grain yields on a sandy soil were of 8470 kg/ha, 12700 kg/ha, and 13000 kg/ha, respectively. Similar data from Robertson et al. (1981), show that for the total water inputs in

1976 of higher than the 30-year rainfall average, and equivalent to average rainfall in 1977, grain yields of corn cultivar Pioneer 3369A were 5100 kg/ha, and 10610 kg/ha, respectively. For 1976, in addition to the larger amount of water input, the rainfall events were such that two events exceeded 9.5 cm between 70 and 80 days after plant emergence, one event exceeded 6 cm, and 5 were between 2 and 3 cm prior to tasseling. For 1977, neither rainfall nor irrigation events exceeded 2 cm.

As a secondary stress, macro-nutrient deficit such as N stress can be produced by a primary environmental stress such as water stress. Additive effects of N and moisture stresses on corn were demonstrated by Reddy et al. (1981). These stresses are similar in the sense that they may induce potentially injurious strains in the plant, either reversibly by inhibiting metabolism and growth, or irreversibly by injuring or killing the cells (Levitt, 1980).

Measurement of Water and N Stresses

According to Greenwood (1976) the term "stress," as used in relation to plants, needs some clarification. It can be defined from the point of view of (1) the status of the stress factor or as (2) the effect of that status on the growth of the plant. This ambivalence of meaning has allowed some scientists to consider stress too broad a term to quantify numerically. Others, confined the meaning of stress to deficit, which clearly separates it from induced plant response.

The plant water stress, as a deficit, is characterized by a decrease in growth and plant water content, total water potential, and osmotic potential, accompanied by loss of turgor, and closure of stomata. A number of different techniques have been used to measure each of these plant variables. The thermocouple psychrometer provides a means of measuring the energy status of water in the plant. It is widely used, being better adapted to laboratory measurements than for general field measurements. As an indirect measure of water content, beta ray gauging is used, but must be calibrated using direct measurements of plant water content such as relative water content.

The relative water content has been indicated as a satisfactory method for field work, having the advantage of allowing comparisons between different periods of stress, or between experiments conducted under different environmental conditions (Shaw and Laing, 1965; and Kramer, 1969).

As a plant response, water stress may be considered to be the result of interactions of a number of factors in the soil-plant-atmosphere system. As an interaction result, the plant response may offer better means of quantitatively comparing periods of moisture stress than plant water status. Begg and Turner (1976) point out that despite the widely accepted concept that crops are more sensitive to water deficits at particular stages of development, it cannot be assumed that the levels of plant water stress are equal within the same experiment. Data reported by Stanberry et al. (1963) illustrate some problems in comparing distinct experiments. Studying sweet corn production

they reported that at pollination, during 1959, despite a soil moisture stress equivalent to that of pollination in May of 1957 and 1958, cool weather and slower transpiration did not result in plant-leaf rolling and wilting. Consequently, the apparent equivalent moisture deficit in 1959 did not cause the same deleterious effect demonstrated in 1957 and 1958. It seems that these and similar data provided by Shaw and Laing (1965) indicate that one of the most important factors to consider in future work is the development of a quantitative means of determining the degree of moisture stress imposed in field experimentation. This would provide a means of quantitatively comparing different experiments.

In the case of nutrient stress, two approaches have been used: (a) nutrient yield response curves and (b) concentration of the nutrient in the plant with respect to a "critical concentration." After discussing the first approach, Greenwood (1976) concluded that nutrient response curves gave very little information about the current intensity of deficiency, and that in some cases might be quite misleading. In the second approach, the plant itself is considered as the integrator of supply and demand. In its graphic expression, yield is plotted against nutrient concentrations in the tissue. The frequent characteristic of this relationship is that, for severe deficiency, yield increases linearly with increase in concentration with a well defined steep slope, whereas at sufficiency, the curve flattens and levels off. At the abrupt change in slope resides the "critical concentration." Below it,

yield is greatly reduced (with very little change in slope), and above it there is very little increase in yield. This is the main form of reference to plant nutrient status in the literature. In 67 N-response experiments conducted throughout the State of Pennsylvania, Fox and Piekielek (1983) concluded that with a concentration of 2.75 % or greater in corn ear leaves at silking, it is highly unlikely that N deficiency would limit yields. However, if the ear leaf N is between 2.2 and 2.75 %, it is not possible to know if N is adequate for maximum yield. Studying the relation between leaf N, P, and K and corn yields, Tiner (1946) tentatively set the critical N, P, and K concentrations of the sixth leaf to 2.90 % N, 0.295 % P, and 1.30 % K. At concentrations above these levels zero or rapidly decreasing response to further applications of these nutrients occurred. Escano et al. (1981a), using four methods to choose optimum tissue nutrient concentrations, obtained similar results. High yields were shown to be obtainable with rather variable ear leaf nutrient concentrations. The adequate ranges found overlapped with most published ranges and included most published critical concentrations. The author concluded that "critical" concentrations alone were not the sole determinants of yield. Pierre et al. (1977) compared a graphical method and a regression analysis for determining maximum yield and the relative yield-% N relationship. Using grain N, they found the critical N percentage to lie in a rather narrow zone, but transitions from the zone of deficiency to the zone of sufficiency were not abrupt. This may be seen as an improvement of the "critical

"concentration" approach mentioned earlier. Escano et al. (1981b), after concluding that relative amounts of nutrients may be more important, used the Diagnosis and Recommendation Integrated System (DRIS) to analyze eight N x P fertilizer experiments. The DRIS is a system of calculations by which ratios of tissue nutrient concentrations in a sample are compared with the "optimum" values of the same ratios in a high-yielding or otherwise desirable population.

Insensitive to variation in local conditions, it has produced more accurate plant nutritional diagnoses than the conventional "critical concentration" approach. Using DRIS based on published optimum ratios of corn earleaf nutrient concentrations as a desirable population, Escano et al. (1981b) obtained an inaccurate diagnosis of N and P fertilizer responses on Hydric Dystrandepts. Their conclusion was that when the DRIS approach based on published ratios gave unacceptably low percentages of correct diagnoses, a local calibration could improve its diagnostic accuracy to levels superior to those of locally calibrated critical concentrations.

Discussing the need to provide quantitative measures of stress, Shaw and Laing (1965) suggested that a technique that could evaluate the interaction between soil, plant, and atmosphere would be the best way of measuring stress. Greenwood (1976), discussing concepts from Goodall and Gregory (1947), concluded that to quantify the degree of deficiency one can measure the magnitude of response of the plant. After considerations about criterion of response, reference point to

represent zero stress, and current growth rates, he formulated a proposition for nutrient stress. The current intensity of a nutrient deficiency--nutrient stress--is defined as the proportion by which the growth rate of the plant or crop is limited by that nutrient under the prevailing circumstances. In addition to the plant response parameter used in the definition (dry weight), leaf elongation, leaf area, CER, and leaf N were proposed for estimating nutrient stress. The later approach can be adapted to any plant nutrient, for temperature, and for water stress studies. A field experiment conducted by Power (1971) indicated that the stress concepts proposed by Greenwood appeared to apply to the quantification of water stress as well as to N stress. His results showed that the growth of grass under dryland conditions in the Northern Great Plains is restricted by both available water and available N. The magnitude of this reduction varies with the soil N availability, water supply, and time. It may vary from practically none to complete cessation of growth. Also, it appears that reductions in growth due to lack of either N or water are additive. As a measurement of degree of stress, it appears a quantitative expression is generally lacking.

Summary

There has been a rapid increase in irrigated agriculture in humid regions, like Florida, where the combination of variable rainfall distribution and low water holding capacity of soils makes the crops subject to water stress at various times

throughout the growing season. Hence, research has concentrated on irrigation of sandy soils and irrigation water efficiencies under different irrigation strategies.

With few exceptions, studies of the nutrient N in sandy soils under irrigation began less than a decade ago. In relation to N, the combination of variable rainfall distribution with low nutrient holding capacity of sandy soils, plus irrigation, was shown to cause plant N stress and loss of fertilizer through leaching. Split applications of N were proven to be a must to avoid possible N stress and minimize leaching losses on sandy soils.

Water percolation losses, N leaching losses, total N uptake at harvest, and final yield (grain and dry matter) under imposed water or N stress have constituted the response variables measured in most studies. None have measured plant responses and their variation throughout the course of the growing season as affected by water and/or N stresses.

The difficulty of comparing experiments, or even stages within the same experiment, when either water or N stresses are applied has been recognized. Questions have been raised due to the fact that the relative sensitivity of different stages of development to stress can vary with the degree of stress.

Compared to plant N stress, the measurement of plant water stress can be considered accurate. With this difference in mind and allowing for high integration power within the soil-plant-atmosphere system, an approach based on plant responses has been proposed in the literature. In addition to

enabling quantification of the degree of deficiency at any time during the course of the growth of the plant, it is applicable to several stress factors.

Water and N have no substitutes in the essential roles they perform in plant development. Increasing production costs have stimulated interest in management practices which will increase water and N fertilizer efficiencies and minimize potential adverse effects on environmental quality.

Corn production on irrigated sandy soils, such as in Florida, subject to variable (unpredictable) rainfall distribution, needs to have predictable N and irrigation water inputs during plant growth. Some degree of stress or loss of either water or N may be impossible to avoid, even under well controlled field conditions.

Thus, research to better understand and measure water and N stress, and improve existing predicting mechanisms is needed. Such research should produce basic information on plant responses to applied treatments (N stress and water stress) throughout the course of the growing season.

CHAPTER 3 MATERIALS AND METHODS

As part of an interdepartmental research project, a field experiment was conducted in 1982 to study the effects of N and water stresses on the development, physiology and yield of corn grown on a sandy soil. The experiment was conducted at the Irrigation Research and Education Park (IREP) on the University of Florida campus, Gainesville. In addition to the data reported here, this study involved other measurements and observations made by Dr. L. C. Hammond (Soil Science Department), Dr. J. M. Bennett (Agronomy Department), and Dr. J. W. Jones (Agricultural Engineering Department). These data and their interpretations will be reported elsewhere by these scientists.

Field Procedures and Materials

The field experiment was conducted in Unit 3B of the IREP as a Complete Block Split-Plot Randomized Design comprised of three water regimes as main-plot treatments, and two fertilizer N levels as sub-plot treatments (Table 1).

The resulting six treatment combinations (W1N0, W2N0, W3N0, W1N1, W2N1, and W3N1) were replicated four times. Fertilizer N applications to sub-plot treatments are given in Table 2.

The soil was a Millhopper fine sand, a member of the loamy, hyperthermic family of Grossarenic Paleudults (Calhoun et al., 1974). General characteristics include a loamy fine sand textural class to a depth of more than 100 cm and a CEC of less than 4 meq/100 g from the surface down to a depth of more than

Table 1. Irrigation and fertilizer N treatments used.

Code	Treatment Description
W1	Irrigation treatment--rainfed, caused the most water-stressed plants. Received irrigation only to ensure germination.
W2	Irrigation treatment--well watered, irrigated when soil-water tension at 15 cm depth reached 0.02 MPa.
W3	Irrigation treatment--same as W2 except for a period of wilting imposed immediately before tasseling. No water inputs between 50 and 66 days from plant emergence.
N0	N treatment--low N, with 116 kg N/ha applied in 3 sidedressings.
N1	N treatment--high N, with 401 kg N/ha applied in 6 sidedressings.

Table 2. Nitrogen sidedressings applied as treatment.

Treatment Code	Date	Days from Emergence	N Applied (kg N /ha)
N1	15 March	7	56
N1	30 March	22	52
NO	7 April	30	27
N1	12 April	35	75
NO	-	-	35
N1	28 April	51	37
N1	7 May	60	55
N1	17 May	70	126
NO	-	-	54

100 cm (Calhoun et al., 1974). Initial (plant emergence) and final (harvest) distributions of nitrate-N and ammonium-N with soil depth were reasonably uniform with depth having an initial total of 51.5 (± 14.5) kg N/ha and at harvest a total of 19.6 (± 4.1) kg N/ha to a depth of 100 cm.

On 23rd February the soil was prepared by disking and roto-tilling. The next day, 1120 kg/ha of a 0-6-25 NPK fertilizer mixture including 6.5% Mg, 0.75% Zn, and 0.25% B were applied to the experimental area. This was followed by nematicide and herbicide applications. Furadan 10G was applied at a rate of 34 kg/ha and a mixture of Sutan + Atrazine at rates of 4.4 l/ha + 2.4 l/ha, respectively. The area was disked after the herbicide application.

On 26th February the experimental site was surface dragged, marked for 61 cm row spacings, and cross marked every 46 cm. Corn hybrid McCurdy 84AA was planted in the marked rows with 23 cm spacing between seeds. This provided a population of 72,000 plants/ha. On 4th March, a 1.27 cm irrigation was applied to the experimental area to ensure good seed germination. Plant emergence was reached by 8th March.

Rainfall and irrigation, as a function of time, are presented in Figure 1. On 9th March, the initial soil sampling was made to measure soil profile distributions of nitrate-N and ammonium-N. All soil samples were immediately oven-dried at 40° to 50° C. The same procedure was followed for soil sampling at harvest.

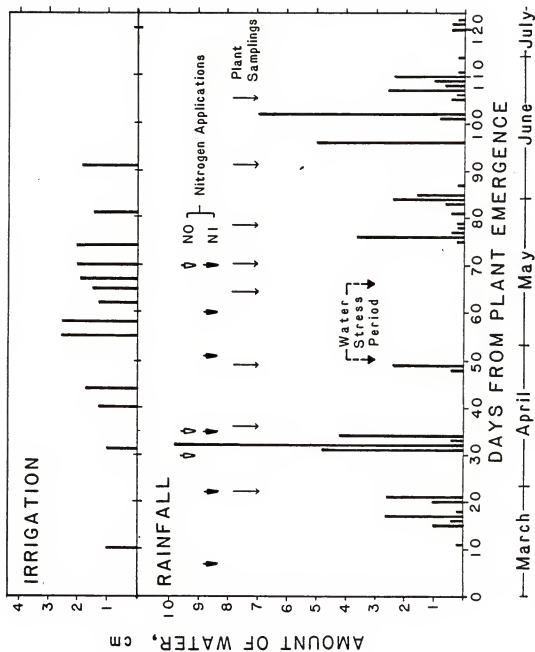


Fig. 1 Rainfall and irrigation distribution and amounts during the growing season at the IREP, U of F campus, 1982. Imposed water stress period, N applications, and plant samplings are indicated by arrows.

On 19th March the plants were thinned to one plant per hill. On 30th March, 22 days from plant emergence, the first plant sampling was conducted. Subsequent plant samplings were made at 36, 49, 64, 70, 78, 91, 105, and 122 days after plant emergence (see Figure 1). Plant samples consisted of the above ground portion of five plants taken from previously selected locations in each plot.

Estimates of when tasseling and silking occurred, under the six irrigation-N treatment combinations, are presented in Table 3. Other observations made at the site include phenological observations, measurements of carbon exchange rate (CER), canopy temperature, actual evapotranspiration, plant water potentials, relative water content, soil-water tension, and soil-water content at various diurnal and/or midday periods. These measurements were made by Drs. J. M. Bennett, L. C. Hammond, and J. W. Jones.

Laboratory Procedures and Materials

Laboratory activities included drying and determining nutrient content in various plant parts.

Plant samples were dried at 65° to 70° C. Of the set of five plants sampled in each plot, the smallest and largest plants were used for estimating biomass. The remaining three plants were divided into their components to measure leaf area, and dry matter distribution between the plant parts, including dead leaves. Numbers of leaves and plant heights were measured for all plants sampled. Dry matter yields in various plant parts were determined after drying at 70° C to a constant weight. All

Table 3. Dates and days after plant emergence for the occurrence of tasseling and silking stages of growth, under the six irrigation-N treatment combinations.

Treatment Combination	Tasseling		Silking	
	Date	Days After Plant Emergence	Date	Days After Plant Emergence
W1 N0	5/24	77	5/26	79
W2 N0	5/13	66	5/16	69
W3 N0	5/15	68	5/17	70
W1 N1	5/16	69	5/24	77
W2 N1	5/08	61	5/12	65
W3 N1	5/10	63	5/13	66

Dates when 50% of the plants were tasseling or silking, based on observations made by Dr.J.M.Bennett.

plant samples were returned to the drier until they were ground to pass a 1 mm sieve. Representative ground plant subsamples were stored in air-tight plastic vials.

Nutrient contents in plant tissues were determined using plant samples that had been oven-dried at 70° C, for at least 12 hours. For total N, P, and K analyses, the plant tissues were digested in a mixture of sulfuric acid, hydrogen peroxide, lithium sulphate, and selenium. Complete digestion of the plant tissue was achieved by heating the contents to 340° C in an aluminum block (Parkinson and Allen, 1975). After dilution, an aliquot was taken to measure N and P concentrations using an automated procedure (Technicon Industrial Systems, 1977). Another aliquot was diluted to allow the measurement of K concentration by flame emission using a Perkin-Elmer 460 atomic absorption spectrophotometer (Parkinson and Allen, 1975). Plant sample weights for digestion and dilution were chosen by estimating N, P, and K concentrations according to the sampling time and plant part (Hanway, 1962b, 1962c).

After drying, the soil samples were ground to pass a 2 mm sieve then passed through a sample splitter. Each soil sample was extracted with 1N KCl (1:10 soil:solution ratio). After shaking for one hour, a 20 ml aliquot was taken from the clear supernatant and ammonium-N and nitrate-N determined using steam distillation with magnesium oxide and Devarda's alloy. The distillates were collected in boric acid indicator, and titrated with 0.005 N sulfuric acid (Bremner, 1965).

Data Processing and Statistical Analyses

Results from a total of 3024 nutrient determinations plus about 1000 replications of these determinations and dry matter data were stored in the IFAS-VAX Computer System. All computations and statistical analyses were carried out using the Statistical Analysis System (SAS, 1983) at the Northeast Regional Data Center (NERDC) of the State University System of Florida. The SAS programs were edited at and submitted to NERDC through the IFAS Computer System.

Preliminary screening of the nutrient percentage data were carried out using MEANS and PLOT procedures to identify "outliers"; these plant samples were reanalyzed.

Nutrient uptake was obtained by multiplying the nutrient content value by the corresponding dry matter yield. Where sums (as in nutrient uptake by whole plants) or means (as in nutrient uptake means by plant part) had to be computed, it was done using the TABULATE procedure. In these cases the output results were not printed at NERDC, but sent back to a file in the IFAS-VAX system. Average or sum values within the same line of data, for plotting purposes, were carried out using the MATRIX procedure.

The fitting of models to the data for dry matter and nutrient accumulations was done using the NLIN procedure. In addition to a summary of non-linear least square statistics, the NLIN procedure produces confidence intervals, a plot of predicted versus observed values, and a plot of the residuals. Whole plant data for dry matter, N uptake, and K uptake, as a function of

time, were fitted empirically using the extreme values distribution function or Weibull distribution

$$Y = Y_{\max} \cdot (1 - \exp(-(X/B)^C)) \quad [1]$$

where Y is the yield response variable (kg/ha) at a given X, the number of days from plant emergence and Y_{max} is the maximum value of the response variable (kg/ha) at harvest, or equivalently when X equals 122 days from plant emergence. The parameter B, referred to in subsequent discussions as the time-response parameter, indicates the inflection point when X=B. By substituting in Eq.[1]

$$Y = Y_{\max} \cdot (1 - \exp(-(1)))$$

$$Y = Y_{\max} \cdot (1 - 0.37) = 0.63 \cdot Y_{\max} \quad [2]$$

Therefore, the time-response parameter indicates the number of days from plant emergence when the dry matter accumulation or nutrient uptake reaches 63 % of the total at harvest. The shape parameter C, referred to here as the shape-reponse parameter, indicates the relative changes in rates of accumulation or uptake as a function of time. The influence of parameters B and C on cumulative Weibull distribution shapes (Eq.[1]) is shown in Figure 2. The range of values used to generate these curves includes those observed in this study. The fitting of Eq.[1] to P uptake data produced irregular distribution of positive and negative residuals, where positive residuals predominated in the first and last third of the curves and negative residuals predominated in the central third. The phosphorus data were best fitted, with balanced distribution of the residuals, by the parabolic equation

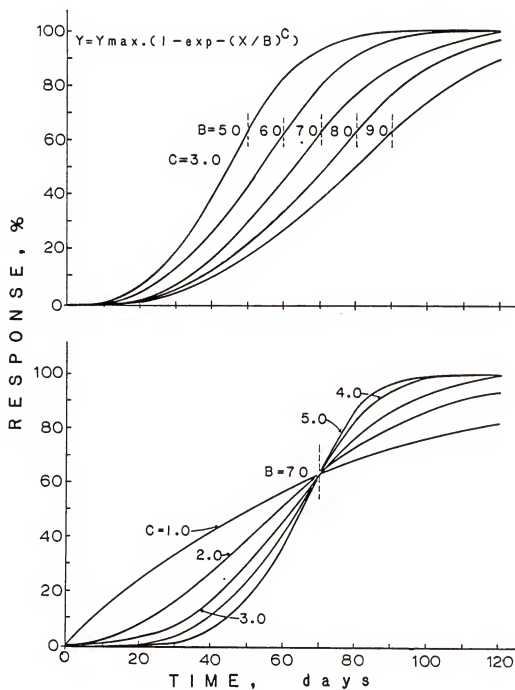


Fig. 2 Shapes of the cumulative Weibull distribution function as influenced by various B and C parameters values.

$$Y = I \cdot X^K \quad [3]$$

where Y is uptake of phosphorus by the plant (kg/ha) at a given time X, the number of days from plant emergence, and I and K, constants.

Absolute rates of crop growth (CGR), N uptake (NUPR), P uptake (PUPR), and K uptake (KUPR) were computed using Eq.[4], the first derivative of Eq.[1]

$$\begin{aligned} dY/dX &= d/dX(Y_{\max} - Y_{\max} \cdot \exp(-X/B)^C) \\ dY/dX &= -Y_{\max} \cdot \exp(-X/B)^C \cdot (-C \cdot (X)^{C-1}/B^C) \\ dY/dX &= Y_{\max} \cdot \exp(-X/B)^C \cdot C \cdot X^{C-1} / B^C \quad [4] \end{aligned}$$

where dY/dX corresponds to the rate of dry matter accumulation or nutrient uptake as a function of time. The equivalent relative rates, RCGR, RNUPR, RPUPR, and RKUPR were computed using Eq.[5]

$$\text{Relative Rate} = (dY/dX) / Y \quad [5]$$

where dY/dX and Y are as defined above.

Nitrogen stress as % reduction in crop growth rate (SNC) or as % reduction in relative crop growth rate (SNR) was computed using Eqs.[6] and [7] (Greenwood, 1976), respectively

$$\text{SNC} (\%) = 100 \cdot (1 - \text{CGR}_{\text{st}} / \text{CGR}_{\text{op}}) \quad [6]$$

$$\text{SNR} (\%) = 100 \cdot (1 - \text{RCGR}_{\text{st}} / \text{RCGR}_{\text{op}}) \quad [7]$$

where rates with subscript "st" represent those of plants under a given N stress condition, N level N0 in this study. Rates with subscript "op" represent those of plants under optimum N condition, N level N1 in this study.

Water stress percentages as percent reduction in crop growth rate (SWC) or as percent reduction in relative crop growth rate

(SWR) were computed by substituting the appropriate rates in Eqs.[6] and [7], respectively (Power, 1971).

Predicted cumulative total N taken up by whole plants, as a function of time and experimental treatments, was computed using the simulation model NITROSIM (Rao et al.,1981). Parameters input values corresponding to each of the six irrigation-N treatment combinations were used, following instructions of the model user's guide (Jessup, personal communication; Table 25). The user's modifiable evapotranspiration subroutine was adjusted to values estimated for the corn growing season (Riestra, personal communication).

Statistical analyses of the effects of irrigation-N treatment combinations on the response variables were made using the ANOVA procedure, with the MODEL statement proper for split-plot arrangement. Whenever the irrigation versus N interaction was significant, a subsequent analysis was carried out using the GLM procedure, where the CONTRAST statements were specified to compare irrigation levels within a N level, and N levels within a given irrigation level. All statistical analyses were done by sampling date. When plant components were involved, all statistical analyses were done by component and by sampling date.

CHAPTER 4 RESULTS AND DISCUSSION

Grain and Dry Matter Yields of Corn

Average values for grain yield, number of seeds per ear, and dry matter yield are presented in Table 4. Results for each experimental unit are given in the Appendix (Table 10). The data in Table 4 show a significant irrigation versus N interaction for both grain yield and the number of seeds per ear. Thus, for both variables, the first column of letters indicates separate comparisons of means between irrigation levels within each N level (N0 and N1), while the remaining three columns indicate comparisons between N levels within each irrigation level (W1, W2, and W3).

The rainfed, most water-stressed, treatment (W1) failed to show a significant difference due to N, while both water-stressed and non-water-stressed (W3 and W2) treatments showed a significant effect on grain yield. Within the high N level (N1), grain yield was sufficiently different for the three cases to be significant. For the low N (N0) treatment, the potential differences were decreased, being significantly lower for only the rainfed treatment.

Corn grain yield was directly proportional to the final number of seeds per ear. As expected, there were no significant differences between seed weights as result of the effects of the irrigation-N treatment combinations. Within the low N level, the

Table 4. Dry matter yield, corn grain yield, and number of seeds per ear as affected by irrigation and N treatments.

Treatment Combination	Dry Matter Yield	Grain Yield	Number of Seeds per Ear
..... kg/ha			
W1 NO	5532 b *	3466ba	229ba
W2 NO	14581 aa	7100aa	343a a
W3 NO	12002 a	7185a a	356a a
W1 N1	7200b	3022ca	220ba
W2 N1	22001a b	12287a b	496a b
W3 N1	17161a	9956b b	474a a

* Means within columns followed by the same letter are not significantly different at the 5 % level according to Duncan's Multiple Range Test. First and second letter columns indicate comparisons within nitrogen levels, while third to fifth columns indicate comparisons within each irrigation level. A significant Irrigation vs. N interaction occurred for grain yield and number of seeds per ear.

comparison of means for number of seeds indicated the same results as for grain yield, where the rainfed treatment yielded a significantly smaller number of seeds per ear. Within each irrigation treatment, the only significant effect of N level was for the non-water-stressed treatment (W2).

Grain yield with optimal water and N (W2 N1) was 19 % lower than the highest reported by Rhoads (1981) on a Florida Ultisol, and 5 % higher than the highest corn yield reported by Hammond et al. (1981) on a Florida Entisol. Water stress induced by no water additions for 2 weeks prior to tasseling caused a 19 % reduction in grain yield, a 5 % reduction in grain number, and a 22 % reduction in dry matter yield.

This water stress caused the plants to show visual stress symptoms for a period of 11 days. For the same corn genotype, Bennett and Hammond (1983) reported a 22 % grain yield reduction from a 2 week stress (wilting) period just prior to tasseling. When the same stress period was terminated three weeks prior to tasseling, the grain yield was reduced by 11 %, as compared to full irrigation (no stress). For a similar number of days with visual stress symptoms, but applied as three drying cycles prior to tasseling, Denmead and Shaw (1960) found a 25 % reduction in grain yield. Limited information has been published on the effects of water and N stress imposed at different growth stages of corn grown on Florida sandy soils. Nevertheless, the available data seem to indicate that stresses under Florida conditions are not unique and that research conducted in other

locations may be used to assess the expected effects of water stress on corn yields under Florida conditions.

The effects of N within each irrigation treatment were identical to those reported by Reddy et al. (1981), who showed a very close relationship between continuous availability of soil water and the response of corn to N.

Dry matter yield (Table 4) showed a similar response to the experimental treatment combinations as number of seeds did, although it did not show a significant irrigation vs. N interaction effect. Water stress under the rainfed condition (W1) significantly reduced dry matter yield in relation to the other two irrigation treatments. The dry matter yield reduction caused by water stress imposed prior to tasseling (W3) was statistically not significantly different from that of the optimally irrigated treatment. Within irrigations treatments, effects of the N level on dry matter were different enough to be significant only where water was not limiting at any time. Relative yields of grain and dry matter under each treatment combination are in close agreement with related data obtained by Stanley and Rhoads (1971).

Total N, P, and K Uptake

The average values for total N, P and K uptake at harvest are presented in Table 5. Detailed results, including dry matter yield, are given in Table 17 through Table 22 in the Appendix. As in the former section, the data in Table 5 are grouped by subplot treatments due to occurrence of significant irrigation vs. N interaction for total N uptake.

Table 5. Nitrogen, P, and K uptake at the maturity, in whole plants as affected by irrigation and N treatments.

Treatment Combination	N uptake	P Uptake	K Uptake
	 kg/ha		
W1 NO	70 ba *	19 d	66d
W2 NO	131a a	52b	141c
W3 NO	113ab a	36c	128c
W1 N1	105b a	25cd	92d
W2 N1	268a b	72a	221a
W3 N1	211a a	57b	170b

* Means within columns followed by the same letter are not significantly different at the 5 % level according to Duncan's Multiple Range Test. For N uptake data, with a significant Irrigation vs. N interaction, letters indicate comparisons as specified in footnote of Table 4.

For the high N level treatment, final uptake of N was significantly lower only under rainfed conditions, where limited crop growth seems to have reduced the demand for N. Within the low N level treatment, the differences between uptake by plants water-stressed prior to tasseling (W3) and those under rainfed conditions (W1) were not large enough to be significant. Within irrigation levels, only plants under no water stress (W2) showed a significant difference due to N. The 268 kg N/ha taken up to produce 12,287 kg grain/ha is in good agreement with the requirement of 135 kg N/ha uptake to produce 6,000 kg grain/ha as indicated by Kurtz and Smith (1966), and with data reported by Bigeriego et al. (1979). By comparing N uptake in Table 5 with grain yield from Table 4, it can be shown that whenever a water or N stress occurred the use efficiency of N to produce grain was decreased.

Phosphorus and K uptake were significantly affected by irrigation-N treatment combinations, as shown in Table 5. Plants stressed for either N (N0) or water prior to tasseling (W3) did not take up significantly different amounts of P between each other. Irrigation treatments showed a stronger effect on P uptake than did N treatments, which may be attributed to the relative immobility of P in the soil. In the case of K uptake, the differences due to water stress were somewhat less pronounced.

The uptake of 72 kg P/ha to produce 12,287 kg grain/ha by non-stressed corn plants is in good agreement (but slightly higher) than the required 28 kg P/ha to produce 6,000 kg grain/ha

(Kurtz and Smith, 1966). Also, it is in agreement with data obtained by Hanway (1962a,b). The uptake of 72 kg P represents 5.8 g P/kg of corn grain compared to the 4.6 g of P per kilogram of grain given by Kurtz and Smith (1966). Water-stress prior to tasseling (W2) did not influence the above ratio, but under the rainfed conditions and high N (W1 N1) it increased (i.e., efficiency reduced) by 40 %. For the low N level, the interaction effect over grain yield started to influence the fertilizer:grain ratio, bringing it very close to the requirements (Kurtz and Smith, 1966) for the treatment W3 N0, where water-stress was imposed prior to tasseling.

Potassium uptake is in agreement with data reported by Rhoads and Stanley (1981) and Hanway (1962b). Although there were significant differences in uptake due to the effects of irrigation and N treatments, K uptake, under the different treatment combinations, showed the same efficiency for grain yield. This was not the case with both N and P uptake.

Nutrient Concentrations in Plant Components

Numerical values for the average concentration of N, P, and K in the plant components, as affected by each treatment combination, are given in the Appendix (Table 11 through Table 16).

Nitrogen

Variations in the concentration of total N in leaves and dead leaves of the corn plants, as a function of time from plant emergence and stresses of water and N, are graphically presented in Figure 3. Statistical analyses indicated a significant

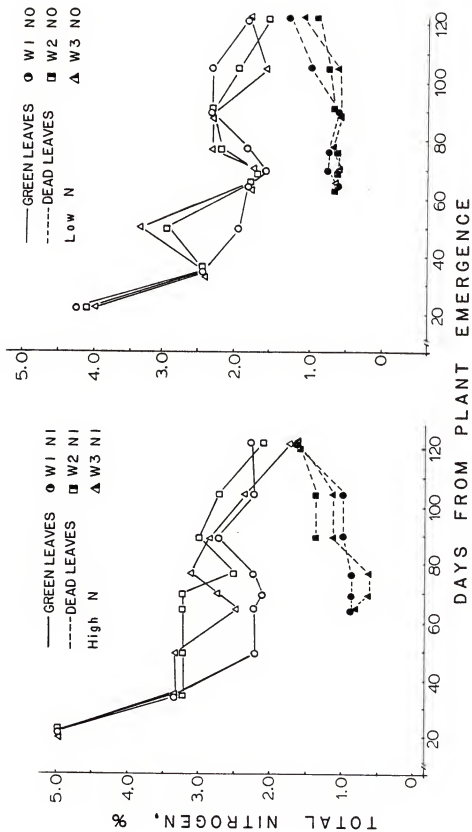


Fig. 3 Total N concentration of green and dead corn leaves as influenced by irrigation treatments and two N levels.

irrigation vs. N interaction effect for the samplings within 45 and 75 days from plant emergence. Also, the largest differences in N concentrations occurred within this period which corresponds to a shift between vegetative and reproductive phases of plant growth. Starting at the second sampling, 36 days from plant emergence, the N concentrations in leaves from all treatment combinations decreased slowly. With exception of the third sampling (49 days) there was a predominance of significant influences of the N factor over those of irrigation. The significant effects of irrigation treatments, when evident, were due to lower N concentrations within the leaves of rainfed, most water-stressed, plants. Significant irrigation vs. N interactions occurred again on the last two plant sampling dates. Near the end of the growing season, the more stressed the plant, the higher was the tendency to show relatively higher N concentrations in the leaves. With the exception of the first sampling date, the concentration of N in the leaves showed a similar pattern to that found in corn leaves by Hanway (1962c). Compared to his data, the first sampling showed values that are higher by approximately 1 % to 1.5 %.

Leaf N concentration values at tasseling, under low N (N₀), are all below the sufficiency level of 2.6-2.7 % indicated by Melsted et al. (1969). Under high N (N₁), only the rainfed, most water-stressed, plants showed lower than the indicated percentage. The prior to tasseling water-stress treatment indicated values that are very close to that sufficiency level.

Together with data for green leaves, Figure 3 shows N concentrations in dead leaves. These were leaves that had senesced either as a result of water and/or N stresses or simply age. The results show that dead leaves, as a result of senescence, occurred in non-stressed plants (W2 N1) for the last three samplings. Nitrogen concentrations tended to approach those of green leaves by the end of the growing season. This fact agrees with the results of Hanway (1962c) who found that leaves at different positions in the corn plant translocated about half of their N content to other plant part(s) prior to senescence.

Total N concentrations in the stem, as influenced by treatment combinations, are presented in Figure 4. The only significant irrigation versus N interaction occurred for the sampling date within the growth stage between the vegetative and reproductive phase. The significant differences were almost exclusively due to N levels. There was a steep decrease in N concentrations for the period between the first (22 days from plant emergence) and fourth sampling date (64 days), which corresponds to the vegetative phase of growth, and concentrations remained approximately constant from this date to harvest, the period corresponding to the reproductive phase. During this phase there was a pattern where the stems from the more water-stressed plants showed a higher N content, namely under low N conditions (N0). This and the related pattern indicated for leaves seems to be due to reduction in translocation caused by stress as reported by Brevedan and Hodges (1973). During the

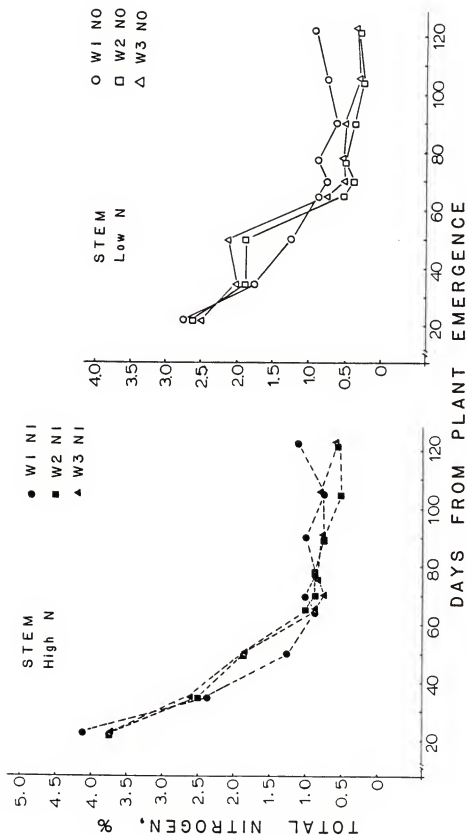


Fig. 4 Total N concentration of corn stems as influenced by irrigation treatments and two N levels.

vegetative growth phase, significant differences in stem N concentrations were chiefly due to N treatments. During reproductive growth the differences were due to both irrigation and N levels. Although there were differences for all sampling dates, these differences in concentration were smaller than those occurring in leaves. Hanway (1962b) reported a similar rapid decrease in % N in the stem during the vegetative phase of corn growth. During the reproductive phase, his data showed a very small decrease with time, which amounted to less than 0.5 %.

Nitrogen concentrations for combined tassels, husks, and silks components of the corn plants, as affected by treatment combinations, are presented in Figure 5. The samples represent a composite of the three plant parts, where tassels predominated in the first two samplings and husks predominated in the last three samplings. Data from Hanway (1962b), for dates equivalent to the last three samplings, showed that N concentrations in tassels and husks were about 1 % and 0.5 %, respectively. Therefore, in a composite sample, the percentages could be expected to vary between 0.5 % and 1 %, as they did in this study. Nitrogen concentrations for the most water-stressed plants (W1) were consistently higher than those of other plants, for both N levels. For most of the dates these differences were significantly different. This feature diverges from that shown by Hanway (1962c), where the most stressed plants (continuous corn), under no fertilization, showed slightly lower concentrations than those from higher fertility treatments. In his case, for a comparable dry matter yield, the final N uptake

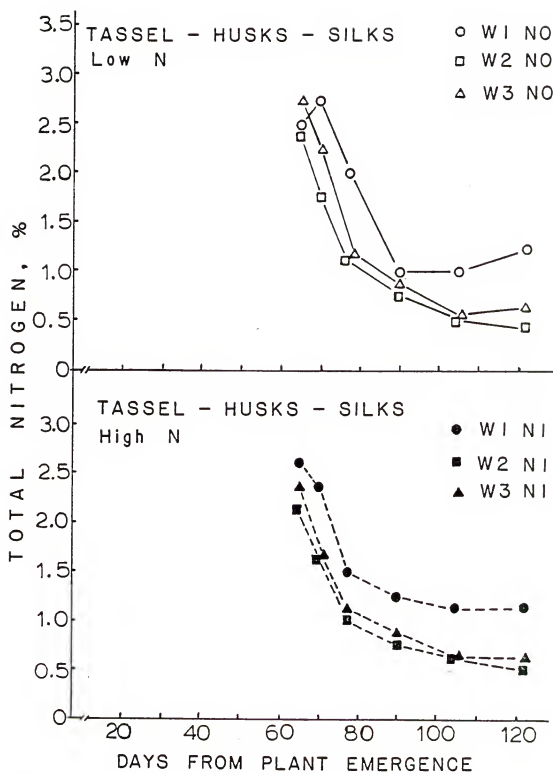


Fig. 5 Total N concentration of composited corn tassels, husks, and silks as influenced by irrigation treatments and two N levels.

was less than half that observed in our case. The higher concentrations reported here may be attributed to the delay in the shift from vegetative to reproductive phase due to water stress, and the continued slow and limited development of the plant N sinks during this phase. If this is the case, it should be true for the other macronutrients in the tassel+husks+silks component.

For the remaining plant parts, cob and grain, N concentrations as influenced by irrigation and N levels are presented in Figure 6. Nitrogen concentrations for cob gave distinctively higher coefficients of variation (CV) for the first four samplings (79, 46, 34, and 32 %, respectively). For the remaining two samplings, the CVs were 20 and 12 %, respectively. For the first two samplings, the lack of significant difference may have been due to the high coefficient of variation. Despite these variations, the pattern of a rapid drop in concentration in the first four samplings (64, 70, 78, and 91 days from plant emergence) and concentrations around 0.5 % for the last two samplings (105, and 122 days from plant emergence) are very similar to the results obtained by Hanway (1962c).

The first N concentration data for grain as a separate part corresponds to 78 days after plant emergence. These data showed the only significant irrigation versus N interaction as well as the dominant influence of irrigation treatments. For the remaining sampling dates, there were significant effects from both main plot and sub-plot treatments, where grain N concentrations were consistently higher for the rainfed

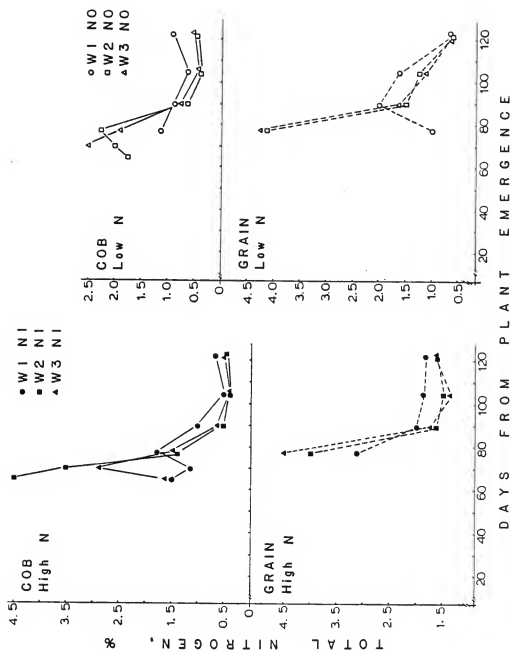


Fig. 6 Total N concentration of corn cobs and grain as influenced by irrigation treatments and two N levels.

treatments, except for the harvest sampling under low N. Under high N, and for the last three samplings, the results are in very good agreement with those of Hanway (1962c), who reported grain data corresponding to the last three samplings only. Under low N, the concentrations of this element continued to decrease, suggesting that there was not enough uptake or enough translocation in the plant system to satisfy the potential of this final sink.

Phosphorus

Statistical analysis of P concentrations in corn plant parts indicated significance similar to those presented for N concentrations.

The effects of experimental treatments on average P concentrations in leaves and dead leaves, as a function of time, are shown in Figure 7. For both N levels, there was a steep decrease in the P concentrations during the vegetative growth phase. Significant irrigation versus N interactions were shown to occur during the shift from the vegetative to reproductive growth phase.

During the reproductive phase, P concentrations increased during the first 10 days, and then remained constant for the low N sub-plots, and decreased for the high N sub-plots. It appears that for the latter case, P was in demand by the grain and was translocated from the leaves in larger quantities than in the former case. Unlike the case for N, P concentrations in corn leaves were only significantly affected by treatments at harvest, and by the N factor during reproductive growth. For this growth

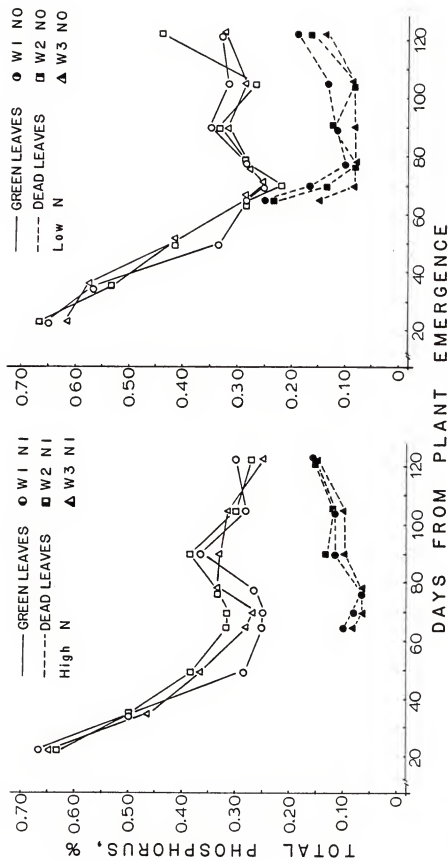


Fig. 7 Total P concentration of green and dead corn leaves as influenced by irrigation treatments and two N levels.

phase, P concentrations were similar to those reported by Hanway (1962c). In relation to the critical corn plant composition values given by Melsted et al. (1969), P concentrations in the leaves, under low N and at the tasseling stage, were within the 0.23 to 0.28 % critical values. Under high N the values were all at or above 0.27 %.

Phosphorus concentrations in stems, presented in Figure 8, showed a significant irrigation versus N interaction at only the last (harvest) sampling. For the comparisons within N levels there was no significant difference between irrigation treatments. Nitrogen treatment comparisons showed significant differences (N0 versus N1) only within the rainfed (W1) and well watered (W2) main-plot treatments. Throughout the growing season there was a significant effect of treatments on the stem's P concentration, which was probably due to the N level. Within the first four samplings there was a decrease in P percentage similar to that shown by Hanway (1962c), but with higher average percentages. As a general trend, the averages under high N were lower than those from the low N plants, indicating a possible dilution effect due to differences in growth throughout the growing season and decreased translocation due to stress.

Results for the P content of the tassel+husks+silks samples are shown in Figure 9. For the first two samplings, where tassel tissues predominated in the sample, the significant differences were mostly due to the N. Concentrations for these samples were about 1.0 % lower than those reported by Hanway (1962c), for comparable samples. Concentration values for the last two

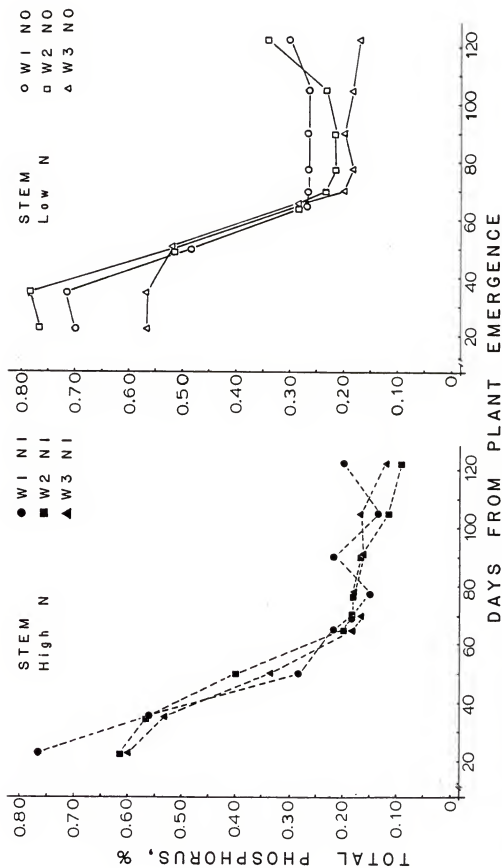


Fig. 8 Total P concentration of corn stems as influenced by irrigation treatments and two N levels.

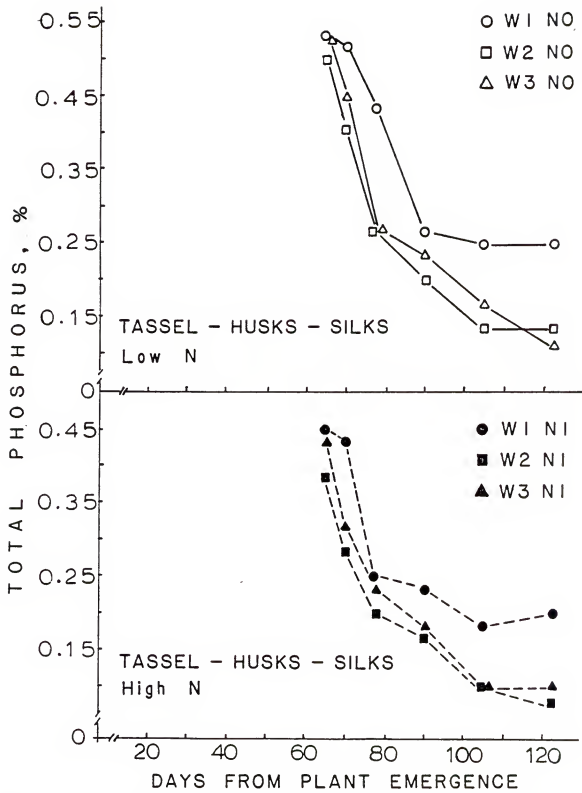


Fig. 9 Total P concentration of composited corn tassels, husks, and silks as influenced by irrigation treatments and two N levels.

samplings, where husks predominated, are in good agreement with the P concentrations in corn husks reported by Hanway (1962c). For the last three samplings, irrigation and N showed a significant difference in P percentage. The previously discussed pattern of higher stress-higher nutrient concentration, due to the possible decrease in translocation within the plant and the concentration effect due to poor growth, is evident (Figure 9).

For the first two samplings, P percentages in corn cobs (Figure 10) showed very high coefficients of variation. Despite the high values for coefficient of variation, there is an indication that N stress, under no water stress (W2N0 vs. W2N1), can cause large differences in P concentrations in corn cobs. The combined effect of N and water stress is evidenced by the rainfed-low N (W1N0) treatment. Data obtained by Hanway (1962c) show that for the last two samplings, the values varied from 0.05 to 0.10 % P.

For both N levels, grain P concentrations showed (Figure 10) the pattern expected based on Sayre's (1948) results. As grain growth accounted for almost all increase in dry weight during the reproductive phase, the dilution effect during times of rapid growth was evident. As P continued to be taken up at increased rates until grain maturity (Hanway, 1962b), an increase in concentration occurred at the end of grain growth. For the last sampling there was a significant effect of N level on P concentration. During the rapid growth stage (grain development) the lower P concentration showed a significant effect due to water stress, mainly for the rainfed treatment under low N.

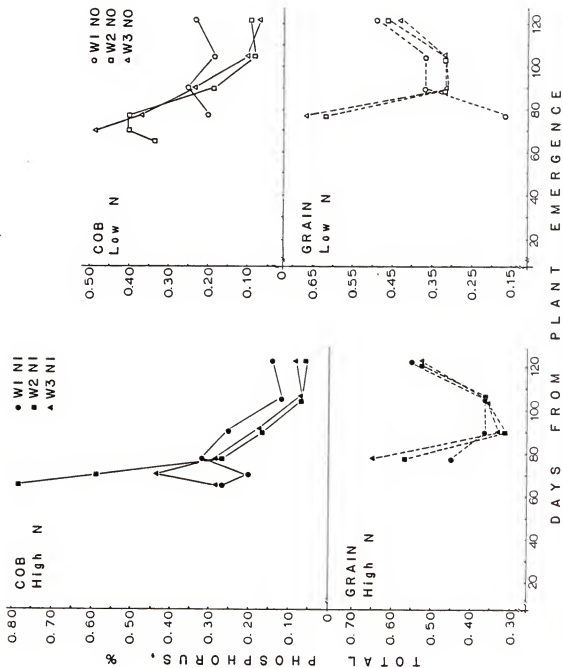


Fig. 10 Total P concentration of corn cobs and grain as influenced by irrigation treatments and two N levels.

Potassium

Coefficients of variation for K concentrations in the various plant parts were below 20 %, with the exception of some stem data. Within N levels, K concentrations in corn leaves of the three water management treatments (Figure 11) did not exhibit significant differences during vegetative growth. Differences, when evident, were due to the effects of N. During the reproductive growth phase, significant effects were due to irrigation and occurred for low N conditions (NO) at harvest and silking (78 days from plant emergence). In these two cases, the rainfed plants (W1) showed significantly higher K concentrations than the other two irrigation treatments. In relation to N and P, the decrease in K as a function of time was very small, as was the case for data reported by Hanway (1962c). An effect of the N level on leaf K concentrations was the higher K concentration in N-stressed plants. For both high and low N levels, the average concentrations for the three irrigation treatments at tasseling stage were above the critical level of 1.9 to 2.1 % leaf K indicated by Melsted et al. (1969).

Potassium concentrations in dead leaves (Figure 11) did not appear to indicate translocation as in the case of N and P. Also, the small decrease in concentration in the leaves as a function of time may be an indication of reduced K translocation within the plant. The average results for K concentrations in stems are presented in Figure 12. In contrast to N and P, K concentrations were at all times higher in stems than in leaves. Statistical analyses indicated significant differences due to N

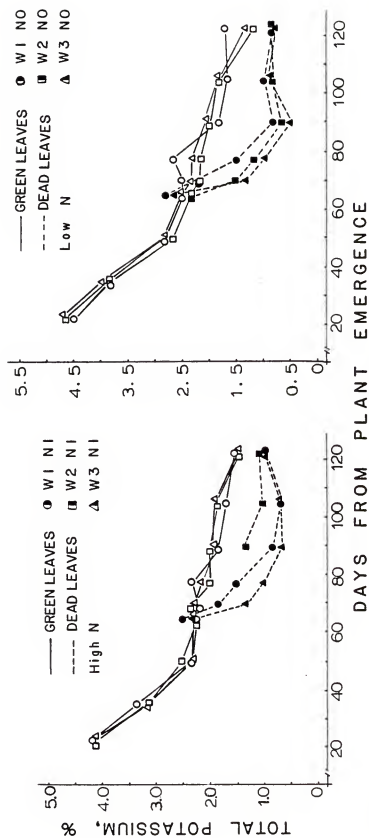


Fig. 11 Total K concentration of green and dead corn leaves as influenced by irrigation treatments and two N levels.

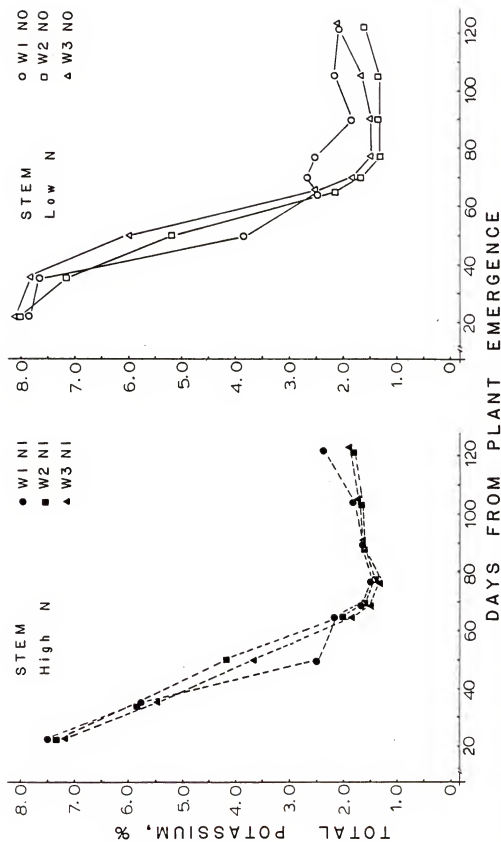


Fig. 12 Total K concentration of corn stems as influenced by irrigation treatments and two N levels.

in the first and second samplings. During the shift from vegetative to reproductive phase, significant differences were due to water stress under low N. There seemed to be no indication of translocation of K, which would cause further decreases in concentration. On the contrary, there appeared to be an increase in K in the stems late in the season.

Potassium concentrations in the composited tassel + husks + silks sample are shown in Figure 13. A significant difference was indicated due to N in the first sampling when the samples were composed of mostly tassels. For the remaining sampling dates the differences were not significant. The tendency for the most stressed plants (W1N0) to show higher nutrient concentrations was also noted.

Cob and grain K concentrations are given in Figure 14. For the first two samplings, when grain could not be separated from the cob due to the very small kernel size, the coefficients of variation were as high as those for N and P. Differences from effect of treatments were not significant. Thus, for these first two samplings, cob + grain was classified as cob. The only significant difference for K concentrations in the cob samples occurred for the samples at 91 days from plant emergence, and was due to the effect of the irrigation under high N (N1). Cobs from the non-stressed plants (W2N1) showed significant lower K concentrations than water-stressed plants (W3N1 versus W1N1). Results for grain are in good agreement with those of Hanway (1962c).

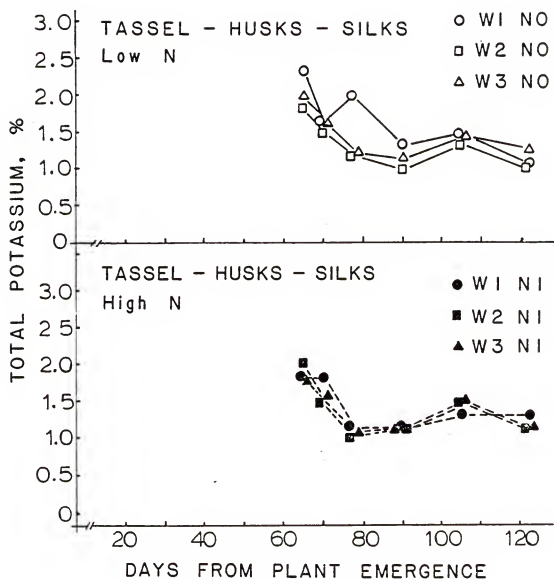


Fig. 13 Total K concentration of composited corn tassels, husks, and silks as influenced by irrigation treatments and two N levels

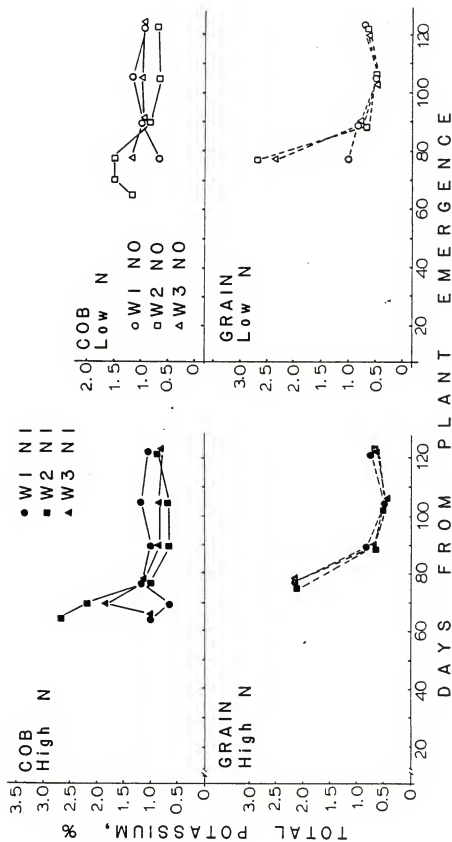


Fig. 14 Total K concentration of corn cobs and grain as influenced by irrigation treatments and two N levels.

Dry Matter Accumulation

Detailed data on plant dry matter accumulation, as a function of time, are given in Table 17 through Table 22, in the Appendix. Each table presents the effect of one of the six treatment combinations on dry matter accumulation, by plant component. Fitted curves to whole plant dry matter accumulation data during the growth season are presented in Figure 15. Statistical analyses for these data, based on whole plants, indicated a significant N treatment effect for plant sampling beyond 35 days from plant emergence. Beyond 50 days from plant emergence, both irrigation and N factors caused significant differences in dry matter accumulation. For the tasseling and silking stages (approximately 65 to 75 days from plant emergence), there was a significant difference for the irrigation versus N interaction which persisted until harvest.

Statistical analysis of dry matter data, based on plant parts, indicated that leaves and stems were the components showing significant differences or treatment interaction effects during the vegetative growth phase and beginning of the reproductive phase, and grain thereafter, up to harvest.

The sigmoid shape curve (Figure 15) was present for all cases, and in varying degrees of expression. Hanway (1962a) fitted linear functions of time to corn dry matter data with additional assumptions to adjust for data at both ends of the growing season. Jordan et al. (1950) reporting on dry matter accumulation of corn suggested that the lower the dry matter accumulation (around 4500 kg/ha) the more pronounced the sigmoid

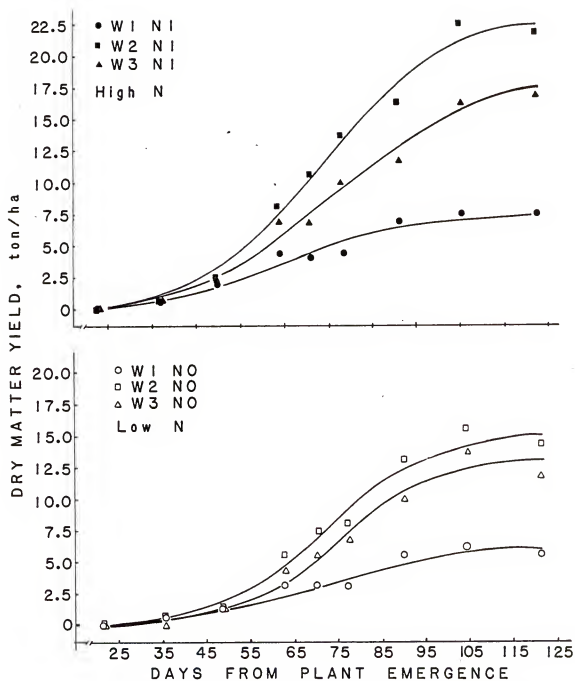


Fig. 15 Whole plant corn dry matter yield as influenced by irrigation treatments and two N levels.

shape of the curves. The closest fit to linearity was shown for curves where final dry matter accumulation approached 13000 kg/ha. Because the work of Jordan et al. (1950) was not curve fitted, interpretation appears to be dependent on subjective judgement. Dry matter accumulation curves (Figure 15) are comparable to those reported by Sayre (1948), where the maximum slope occurred at the end of vegetative and beginning of reproductive stages. As a general pattern, there were larger differences due to irrigation than to N.

Table 6 presents average values of parameters for the model fitted to the data and the statistical comparisons. The maximum response parameter (Y_{max}), given in kg/ha, is equivalent to dry matter means reported in Table 4. Significant differences were observed for both irrigation and N. The time-response parameter (B) values, given in units of days, were statistically not different even though there was a shorter time-response (10 days) for the plants under the rainfed-high N combination (WIN1) to reach 63 % of their final response in terms of dry matter accumulation. It seems that these plants were not as well balanced as when both stresses, water and N, were affecting the plants. Except for this case, the data (Table 6) are in very good agreement with data of Jordan et al. (1950) with respect to time elapsed to reach 63 % of the final dry matter accumulation response. For different N application rates and no apparent water stress, they indicated 77 to 81 days for corn plants to reach 60 % of their total dry matter production. Similar data from Hanway (1962a) indicated 77 to 80 days after plant

Table 6. Parameters of the model $Y = Y_{\max}(1 - \exp(-(X/B)^C))$, fitted to the dry matter data, as affected by irrigation and N treatments.

Treatment Combination	Parameters		
	Ymax (kg/ha)	B (days)	C
W1 NO	6192a*	77.1	3.63 b
W2 NO	15338b a	79.2	4.26a
W3 NO	12913c	80.9	4.50ab
W1 N1	7551 b	71.8	3.24
W2 N1	22997 ab	81.3	3.73
W3 N1	17574 a	81.5	3.52

* Means within columns followed by the same letter are not significantly different at the 5 % level according to Duncan's Multiple Range Test.

emergence. Significant differences were indicated for the shape-response parameter (C), but only due to the irrigation factor, and then only under low N (N0).

The degree of expression of the sigmoidal curve for the rainfed (W1) treatment was significantly lower than the effect of no water-stress (W2) and water-stress prior to tasseling (W3). As will be further discussed, it seems that the shape parameter was related to the rate of change in slope of the accumulation curve. The higher the C value, the larger the relative changes in the slope of the accumulation curve. The data on dry matter accumulation, by plant parts (Table 17 through Table 22, in the Appendix), indicated translocations within the plant under high N (N1), irrespective of irrigation treatment. Despite this, the lower the water stress, the more evident was the translocation from stems.

Cumulative Nutrient Uptake

Uptake of each of these macronutrients by corn, as a function of time, is presented in Table 17 through Table 22, in the Appendix. Each table presents data as affected by one of the six irrigation-N combinations.

Nitrogen

Nitrogen uptake as a function of time, for whole plants, is presented in Figure 16. The curves are the result of fitting the model, described in Chapter 2, with the data points indicated in the figure. The model parameters and results of their statistical analyses are given in Table 7. Despite the absence of significant differences, the change in values of parameter C

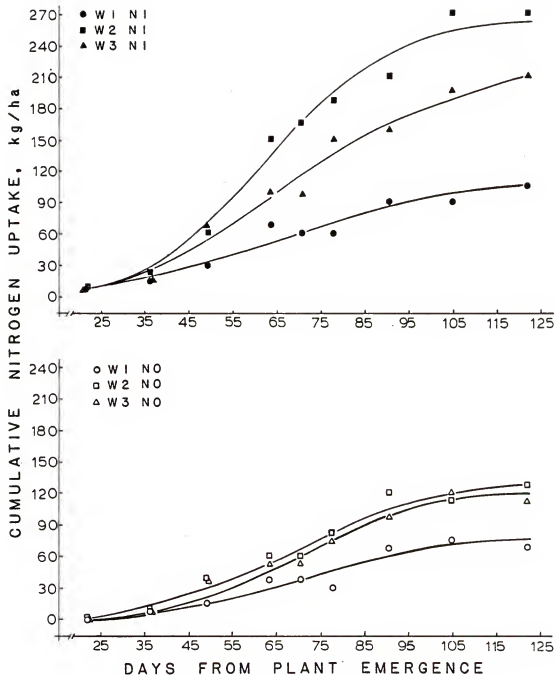


Fig. 16 Whole plant cumulative N uptake by corn as influenced by irrigation treatments and two N levels.

are well illustrated by the respective changes in the shape of the N uptake curves (Figure 16). As indicated by the values of parameter B, stresses in either water or N indicate a tendency for the number of days to reach 63 % of total N uptake to increase. The range of values is very similar to that presented by Hanway (1962b), with the best growth conditions giving the smallest B values. With the exception of plants under treatment combinations involving the rainfed condition (W1), all reached 63 % of total N uptake after silking.

Rhoads and Stanley (1981) reported 60 % uptake at about 8 weeks after planting or 46 to 50 days after plant emergence, while Robertson et al. (1973) reported 60 % of total N uptaken by corn at 60 to 74 days after emergence. For the first case the data were based on about 81 days of growth and do not seem to be comparable to the present case, which is based on positive N uptake to at least 105 days. Only the maximum response parameter (Y_{max}) showed a significant difference, as indicated in Table 7. Averaging over irrigation treatments, the data show the same trends as those reported by Jordan et al. (1950).

Examination of the data for N uptake by plant parts (Appendix) indicates considerable translocation of N from the leaves toward the grain. For stems, with exception of the treatment combination involving rainfed-low N (W1N0), there is evidence of the translocation into the grain. Sayre (1948) observed trends in N accumulation similar to those of dry matter.

Table 7. Parameters of the model $Y = Y_{\max}(1 - \exp(-(X/B)^C))$, fitted to the N uptake data, as affected by irrigation and N treatments.

Treatment Combination	Parameters		
	Ymax (kg/ha)	B (days)	C
W1 NO	85 *	84.2	2.88
W2 NO	158 a	83.9	3.03
W3 NO	120	76.3	3.28
W1 N1	130 b	85.6	2.57
W2 N1	269a b	72.0	3.04
W3 N1	227ab	78.2	2.77

* Means within columns followed by the same letter are not significantly different at the 5 % level according to Duncan's Multiple Range Test.

Phosphorus

Phosphorus as a function of time, by whole plants, is presented in Figure 17, where fitted curves are also shown. The accumulation pattern for P is different than the pattern for the other nutrients. Phosphorus uptake increased with time up to harvest. Values for the parameters of the fitted model are presented in Table 8. Statistical analyses of the parameters did not indicate significant differences, but the tendency is evident (Figure 17). Limited data from Chandler (1960) and data corresponding to medium and low N supply from Jordan et al. (1950), indicate similar trends. Hanway (1962b) indicates a sigmoid pattern for all cases.

Uptake by plant parts (Appendix) indicates large translocations from the husk and cob to the grain. There is no evidence of net translocations from the leaves, which maintained their maximum uptake through maturity. Increases in the degree of water or N stress show a progressive decrease in translocation from the stem.

Potassium

As for dry matter and N accumulation, K uptake (Figure 18) showed a sigmoid pattern for all cases. Model parameters are presented in Table 9. Besides the statistical differences indicated for the maximum response parameter (Y_{max}), the time-response parameter (B) and the shape-response parameter (C) show rather distinguishing values for N and dry matter accumulation. The effect of the differences in values are apparent in Figure 18. For this case, the number of days after

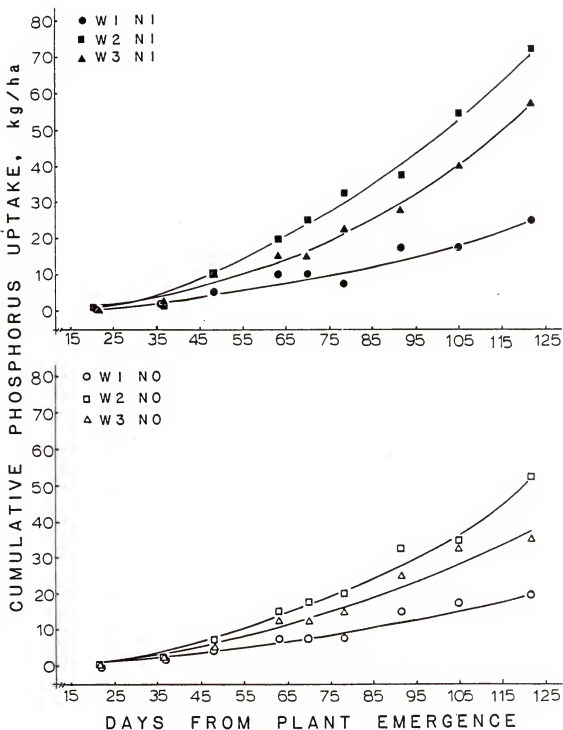


Fig. 17 Whole plant cumulative P uptake by corn as influenced by irrigation treatments and two N levels.

Table 8. Parameters of the model $Y = I \cdot (X)^K$, fitted to the P uptake data, as affected by irrigation and N treatments.

Treatment Combination	Parameters	
	I	K
W1 N0	0.0172	1.608
W2 N0	0.0074	2.032
W3 N0	0.0057	1.876
W1 N1	0.0404	1.741
W2 N1	0.0101	2.010
W3 N1	0.0063	2.218

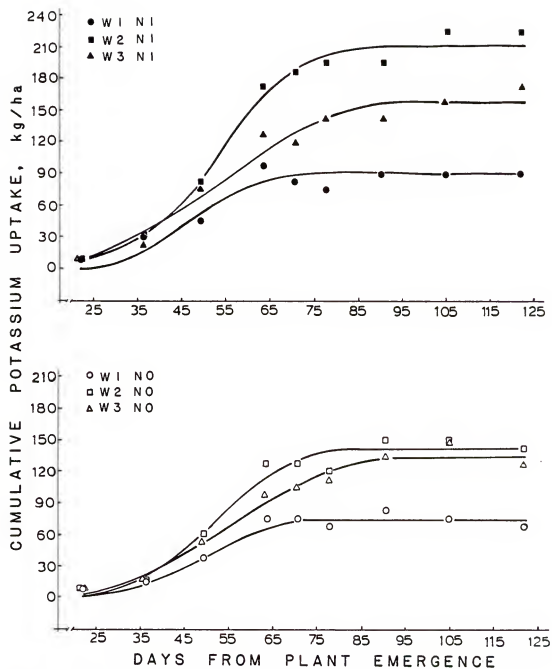


Fig. 18 Whole plant cumulative K uptake by corn as influenced by irrigation treatments and two N levels.

Table 9. Parameters of the model $Y = Y_{\max}(1 - \exp(-(X/B)^C))$, fitted to the K uptake data, as affected by irrigation and N treatments.

Treatment Combination	Parameters		
	Ymax (kg/ha)	B (days)	C
W1 NO	74ba *	51.6	4.77
W2 NO	146a a	57.7	4.40
W3 NO	135a a	60.0	4.25
W1 N1	90aa	51.4	4.24
W2 N1	219b b	59.8	4.42
W3 N1	157c a	56.9	3.60

* Means within columns followed by the same letter are not significantly different at the 5 % level according to Duncan's Multiple Range Test. Effects on Ymax showed a significant Irrigation vs. N interaction.

emergence required to reach 60 % of the maximum response is considerably smaller, while the values of the shape-response parameter are higher than most previous cases. By relating the number of days from plant emergence for 60 % of final response to the number of days to reach final response levels, it can be shown that, within the high N level (N1), final response was reached 25 to 35 days after that for the 60 % response. For the low N level (N0), the final response was reached 20 to 30 days after that for 60 % of total response. In both cases, water stress prior to tasseling (W3) caused a delay, in days, suggesting more imbalance within the plant due to the relatively mild stress. These data are in good agreement with much of the published data (Sayre, 1948; Jordan et al., 1950; Hanway, 1962b). The pattern of K translocation is the same as published data, as indicated in the data for plant parts presented in the Appendix. Much of the K translocation seems to occur from the leaves, where part of it is translocated to the seed and part to the stem.

Corn Crop Growth Rates

Absolute and relative crop growth rates, as affected by treatment combinations, are presented in Figure 19 and Figure 20, respectively. Although they were estimated from a continuous function, as detailed in Chapter 2, the data points identify the values of the respective rates at the sampling dates. The numerical values of these data points are presented in the Appendix, where Table 23 presents absolute crop growth rates (CGR), and Table 24 presents relative crop growth rates (RCGR).

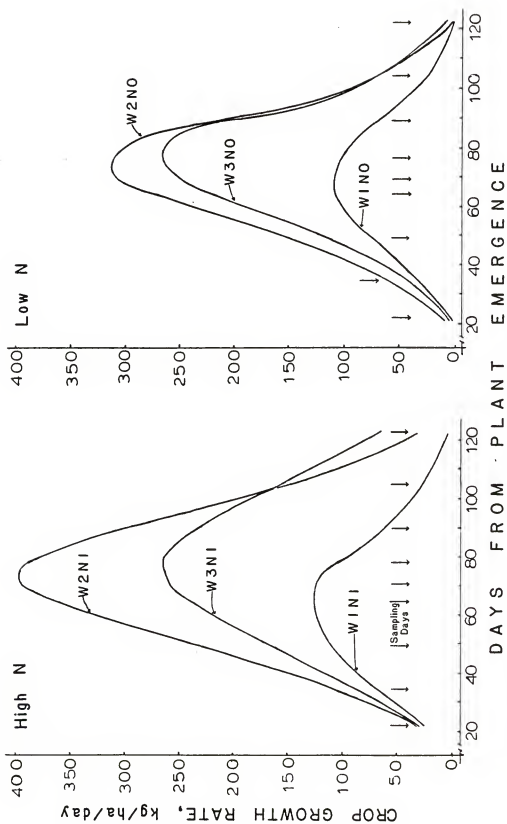


Fig. 19 Crop growth rates (CGR), computed from fitted curves, as influenced by irrigation treatments and two N levels.

Statistical analyses of CGRs indicated significant differences and interaction effects. Coefficients of variation decreased from the first sampling (36 %), 22 days after plant emergence, to the sixth sampling (7.6 %), 78 days after plant emergence. It increased considerably during the last three sampling dates going from 22 to 149 %.

The increase in CV is probably due to the large variation in data for the last two samplings (61 and 149 %, respectively). At 22 days from plant emergence the CGRs showed a significant N effect. At 36 days, following a week without rainfall (Figure 1), the water stress treatments started to show a significant effect together with the N stress. This behavior continued in subsequent samplings. For the next three samplings, starting with that within the imposed water stress prior to tasseling (64 days after emergence), a significant irrigation vs. N interaction was observed. The last significant effect, 91 days after plant emergence, was due to the irrigation, with significant different rates between the three levels. The number of days at which the growth rates reached their maximum seemed independent of N but dependent on irrigation.

Other than occurring earlier, by 3 to 10 days, no relation was found between the time-response parameter (B) previously discussed and the day when maximum rate was observed. The rainfed, most water-stressed, plants (W1) reached their highest rates of growth during vegetative growth, while the less water-stressed (W3) and non-water-stressed plants (W2) had higher growth rates after silking. Of the growth rates reported in the

literature (Hanway, 1962a; Jordan et al., 1950; and Sayre, 1948), the closest to those observed in this study (392 kg/ha/day) was that of Chandler (1960), with 347 kg/ha/day. Even for comparable total dry matter production, the CGRs reported in the literature are somewhat lower. It is apparent that the lower rates are due to fitting linear instead of non-linear models as recommended by Radford (1967) and Hammond and Kirkham (1949). From the data points reported by Hanway (1962a) it is possible to verify that maximum rates occurred immediately after silking, as is the case in our data, for both N levels, with the exception of the rainfed plants (W1).

The relative crop growth rates (RCGR), presented in Figure 20, showed a lower significant difference than the CGRs. This should be expected because RCGR changes were less than CGR over the life of a crop by an order of magnitude (Greenwood, 1976). Coefficients of variation were about 10 % for all sampling dates, except the last two (105 and 122 days from plant emergence) where CVs. were comparable to those of CGRs (54 and 135 %, respectively). For the first two sampling dates, significant differences were due to N. For the next four samplings, the differences were due to both irrigation and N. Under high N conditions (N1), the relative growth rates for the rainfed (W1) and prior-to-tasseling water-stressed plants (W3) showed the expected trend, but significant differences started to occur only around 70 days after plant emergence. Under N stress (N0), there were no significant effects on RCGRs between well-watered (W2) and prior-to-tasseling water-stressed plants. The general

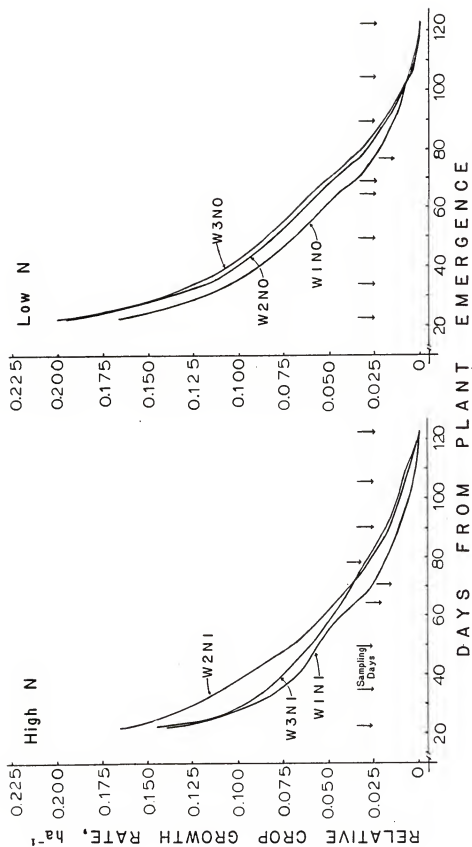


Fig. 20 Relative crop growth rates (RCGR), computed from fitted curves, as influenced by irrigation treatments and two N levels.

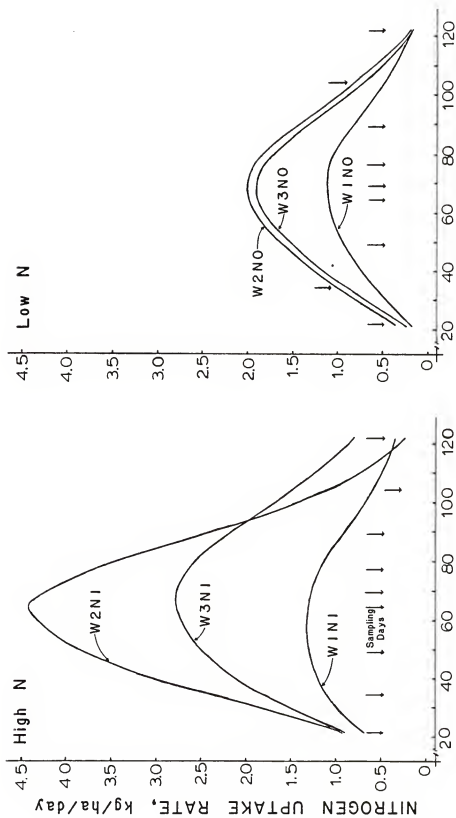
decline of RCGRs, as a function of time, in all treatments is attributed to the proportional decrease of assimilatory tissue with time (Halse et al., 1969). The constant lower RCGRs for well-watered high N plants (W2 N1) in relation to the RCGRs of well-watered low N (W2 NO) were an unexpected trend, which requires the assumption that the N-stressed plants can sustain higher RCGR than non-N-stressed ones. Based on additional data collected during this experiment (as mentioned in Chapter 2), there was less competition for light (lower Leaf Area Index, LAI) between plants under low-N conditions (NO) than under high-N (N1).

Nutrient Uptake Rates and Stress Indices

The absolute and relative rates of N, P, and K uptake are presented in Table 23 and Table 24, respectively, in the Appendix. Although the data are shown at the tables as discrete points in time, they are derived from a continuous time function that was individually fitted to the data for each treatment combination as described in Chapter 2. In general, these data differ from most of the published ones by being fitted to non-linear models and not being an average between two or more sampling dates.

Nitrogen

The absolute N uptake rates (NUPRs) by corn under each treatment combination are shown in Figure 21. The data points correspond to the day of plant sampling after plant emergence. Indicate significant differences for irrigation versus N interaction. For the first sampling date the analysis indicated



DAYS FROM PLANT EMERGENCE

Fig. 21 Nitrogen uptake rates (NUPR), computed from fitted curves, as influenced by irrigation treatments and two N levels.

significant effects for both irrigation and N factors. For both N levels, the non-water-stressed plants (W2) showed significantly higher NUPRs than the rainfed. For any irrigation level, the NUPRs were significantly affected by the N level. From 90 days from plant emergence till harvest (122 days) there were no significant differences; however, as for the crop growth rate data, the coefficients of variation were as high as that for the CGRs. Despite the variation, there was a strong tendency for differences due to irrigation. The maximum NUPR of 4.4 N kg/ha/day occurred 64 days after plant emergence under well watered high N conditions (W2 N1). With similar grain yield production, Rhoads and Stanley (1981), by averaging the data between 6 and 13 weeks, reported NUPRs of 3.0 to 3.1 N kg/ha/day. Values of 3.5 to 3.8 N kg/ha/day can be estimated from data in their report when averaging over a two weeks period. Bigieriego et al. (1979) reported N uptake rates of 4.5 N kg/ha/day around 62 days after plant emergence. For most cases there is difficulty in comparing rates with those from the literature due to long term averages. In spite of this difficulty, the occurrence of maximum N uptake rates prior to those of dry matter accumulation is in good agreement with what can be observed from plots given by Hanway (1962a; 1962b). The only exception to this general trend occurs with the plants under rainfed-low N, where the maximum rates seems to occur around the same time after emergence.

The relative rates of N uptake, presented in Figure 22, showed a trend similar to those for relative crop growth rates, but with much less significant effects than those found for the latter. The significant effects were only due to the N and occurred for the three samplings within 60 and 80 days after plant emergence. The coefficients of variation were analogous to those observed in the NUPRs. Throughout the growing season, in addition to the significant effects within 60 and 80 days after plant emergence, there was a tendency for the RNUPRs under high N (W1) to be lower than that for plants under low N (NO). This seems to suggest that N-stressed plants have a tendency to take up N more efficiently. This characteristic helps explain the higher RCGRs for N-deficient plants in relation to well supplied ones.

Phosphorus

Phosphorus uptake rates (PUPRs) are presented in Figure 23. Values for each day of sampling in Figure 23 are presented in Table 23, in the Appendix.

Differences in effect of treatment combinations on P uptake were shown to be significant throughout the growing season. For samplings within 30 and 65 days after plant emergence there were significant irrigation versus N interactions. In addition to the statistical analyses results, the data depicted in Figure 23 allow for the visual nature of the interactions. For the first 25 days after plant emergence the significant differences were due to irrigation effects. Between 70 and 110 days there were significant differences due to both irrigation and N. Compared

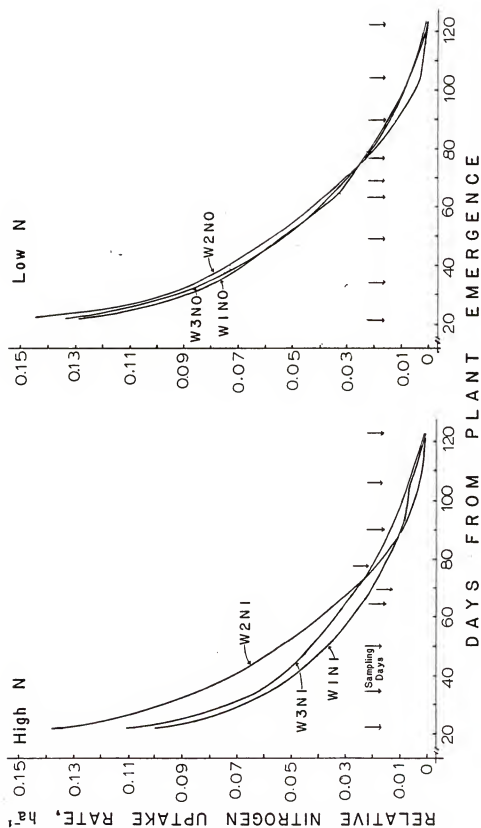


Fig. 22 Relative N uptake rates (RNUPR), computed from fitted curves, as influenced by irrigation treatments and two N levels.

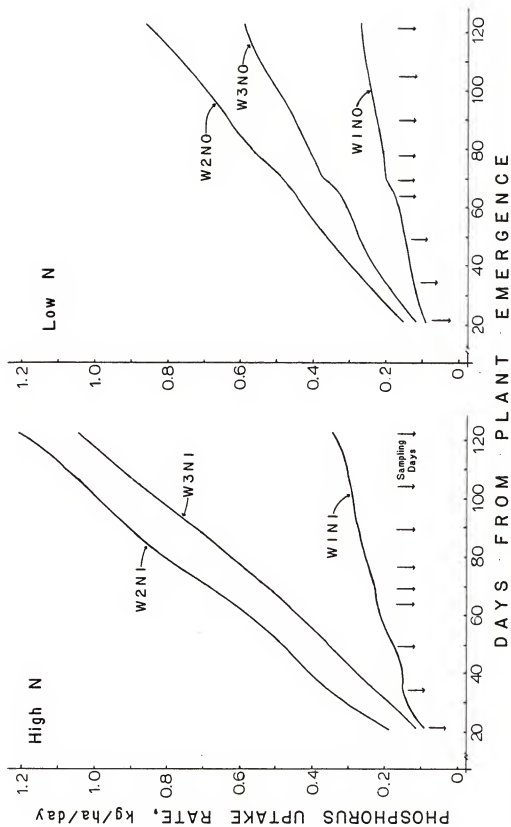


Fig. 23 Phosphorus uptake rates (PUPR), computed from fitted curves, as influenced by irrigation treatments and two N levels.

to the other rates data, P rates showed relatively constant coefficients of variation throughout the growing season. All treatment combinations showed increasing rates as a function of time, up to the last sampling (harvest). This trend is also apparent in data from Jordan et al. (1950) and Hanway (1962b), but in cases where there is some degree of N or nutrient stress. For relatively well fertilized plants, the rates are apparently identical to those shown in the previous section for N. The ever increasing rate appears to be a behavior that should be expected because for most cases 70 to 85 % of the total plant phosphorus uptake was translocated to the grain (Table 17 through Table 22, in the Appendix). These high P proportions in corn seeds are reported in data presented by Sayre (1948), 75 %, Chandler (1960), 83 %, Jordan et al. (1950), up to 80 %, and Hanway (1962b), with 72 to 82 %, including N stressed plants. The maximum final rate of P uptake varied from the most stressed plants (W1 N0), with 0.28 P kg/ha/day, to the non-stressed plants (W2 N1) with 1.23 P kg/ha/day. Chandler (1960) reported a maximum rate of P uptake by corn of 1.0 P kg/ha/day, which occurred at about 15 days prior to harvest, for a final grain yield of 7862 kg/ha. For grain yields of 7200 kg/ha and 9955 kg/ha, our data indicated maximum rates of 0.9 P kg/ha/day and 1.1 P kg/ha/day, respectively.

The relative rates of P uptake (RPUPRs), presented in Figure 24, with trends opposed to those for RCGRs and RNUPRs, show a decrease in relative uptake rate with an increase in stress. None of the effects were different enough to show statistical

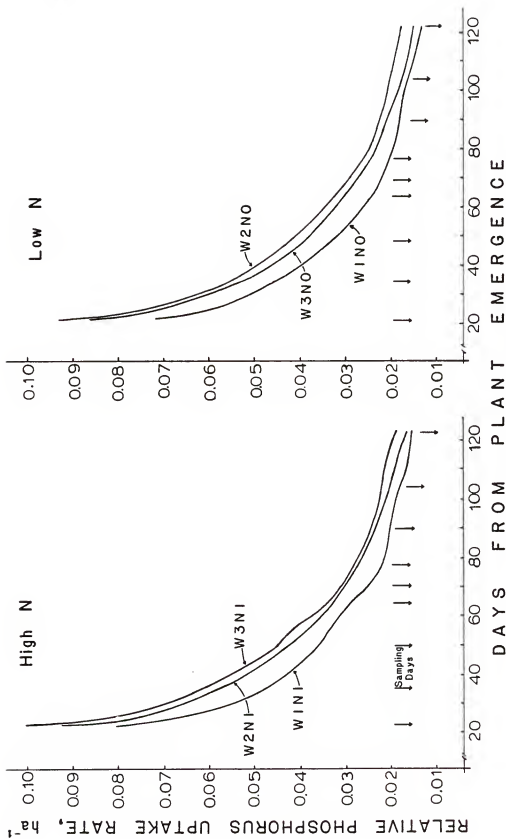


Fig. 24 Relative P uptake rates (RUPPR), computed from fitted curves, as influenced by irrigation treatments and two N levels.

significance. This trend confirms evidence, discussed under the second section of this Chapter, that the ratio of total plant P uptake to grain yield is almost constant, despite the large differences in grain yields.

Potassium

The effect of the treatments on the rate of K uptake by the plant (RKUP), presented in Figure 25, showed a pattern that differs from those of N and P in that the rates are not constant throughout the growing season. The numerical values for the data points in Figure 25 are presented in Table 23, in the Appendix. One significant irrigation versus N interaction was noted by the statistical analyses and occurred for K uptake at the second sampling (36 days after plant emergence). For samplings within 45 and 80 days after plant emergence there were significant differences due to irrigation. The time at which maximum K uptake rates occurred (Figure 25) seems to reflect the effect of irrigation. Also, for plants stressed prior to tasseling (W3), there was a different effect due to N, where the no N-stressed (N1) plants reached maximum uptake much later (about 20 days) than the N-stressed plants. The maximum KUPR of 5.8 K kg/ha/day was found under the well watered-high N treatment combination (W2 N1) and agrees with the peak rate of 5.7 K kg/ha/day found by Chandler (1960) in North Carolina. Jordan et al. (1950) found the maximum K uptake rate to be 2.5 K kg/ha/day in Mississippi for non stressed plants. His averaging over 21 days to compute the rate seems to be the cause of the low rate reported, as rates seem to vary rapidly with time near the maximum rate.

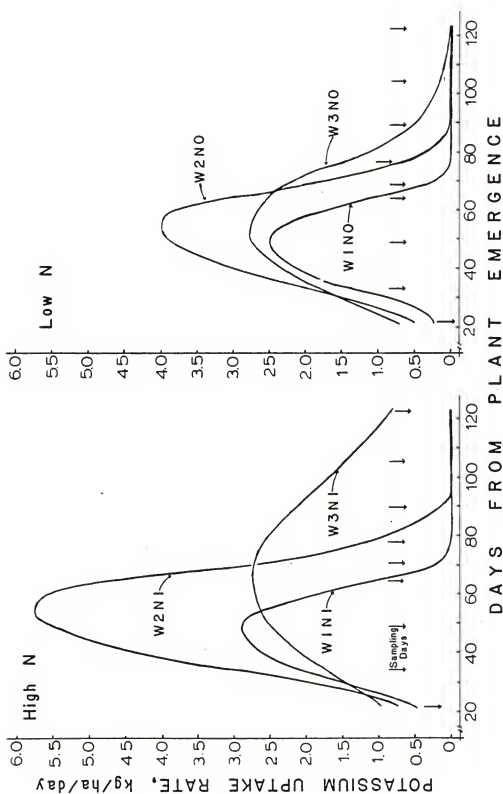


Fig. 25 Potassium uptake rates (KUPR), computed from fitted curves, as influenced by irrigation treatments and two N levels.

The relative K uptake rate (RKUPR) is shown in Figure 26. Numerical values corresponding to the data points are given in Table 24, in the Appendix. The coefficients of variation for RKUPRs were very similar to those found for N. Effects of treatment combinations were not different enough to be significant. Nevertheless, the pattern found in the RCGRs and RNUPRs was also present in the RKUPRs, where N stress seemed to have enhanced the relative uptake ability of the plant. The rapid decline in the relative K uptake rates within 70 days from plant emergence constituted a sole characteristic for the RKUPRs.

Nitrogen Stress

Based on relative growth rates, the N stress percentage (SNR) values, shown in Figure 27, do not seem to indicate % decrease in growth due to N stress. These values did not show a similar trend to that reported in studies using stress measurement concepts discussed by Greenwood (1976). SNR becomes positive only after 90 days from plant emergence (Figure 27). Considering the RCGRs in Figure 28 and how SNR is computed (Chapter 2), negative values should be expected. Although the same principle for measuring the proportion by which the growth rate of the plant falls short of the maximum growth rate was used, the same technique to obtain reduced rates of growth were not used. Greenwood (1976), Halse et al. (1969), and Power (1971), applied the SNR computation model to differences in RCGR after a deficient plant received a non-limiting supply of the factor (N) causing the deficiency. Thus, they evaluate how the rates change (and not fall short of the maximum, as in the

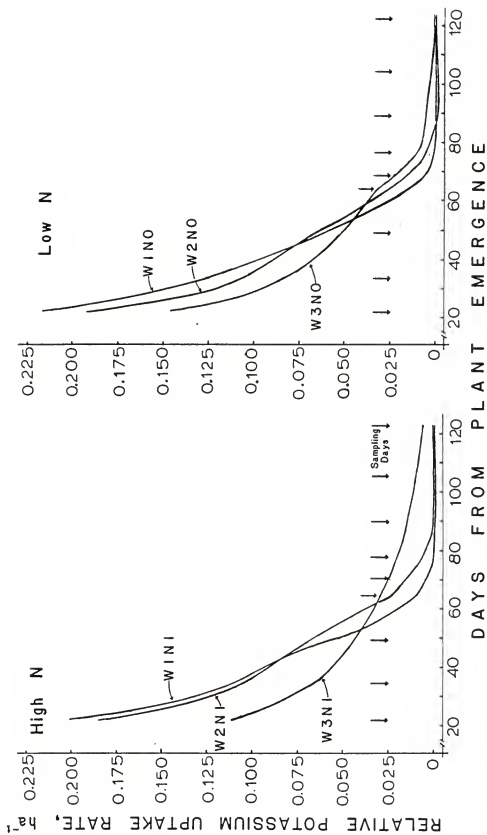


Fig. 26 Relative K uptake rates (RKUPR), computed from fitted curves, as influenced by irrigation treatments and two N levels.

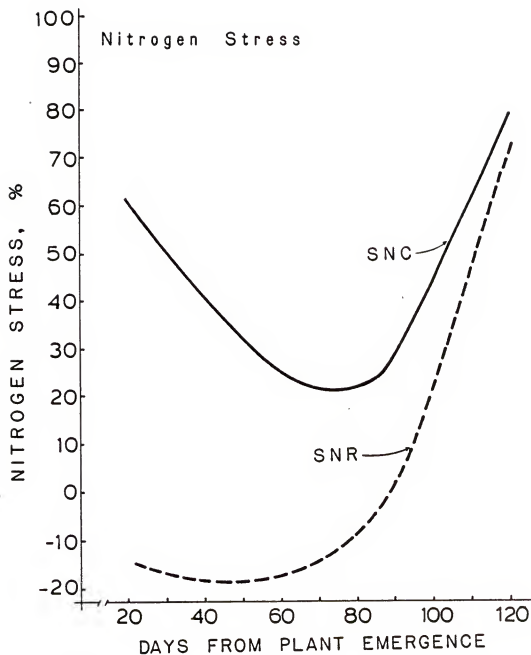


Fig. 27 Corn N stress percentage based on absolute crop growth rate (SNC), and N stress percentage based on relative crop growth rate (SNR) computed by use of growth rates under treatments W2N1 and W2N0.

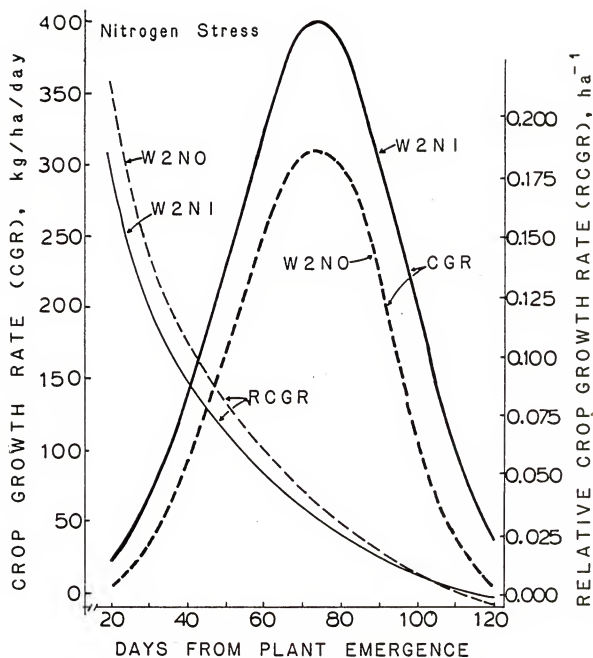


Fig. 28 Growth rates used to compute corn N stress based on absolute crop growth rates (SNC) and N stress based on relative crop growth rates (SNR) of plants under treatments W2N1 and W2N0.

concept) after cessation of the limiting factor. The authors always obtained increases in the relative growth rates over the period of measurement (2 to 3 weeks), and negative values occurred only as a result of experimental, mostly non significant, variation at low levels of deficiency (Power, 1971). This technique seems to be adequate for perennial or semi-perennial crops where the system may benefit from such measurements by further corrective measures. For annual crops in high yield systems it seems reasonable to assume that any estimate of stress should be related to conditions when high yields are anticipated. Also, as discussed previously, and shown in Figure 28, plants under stress seem to have a higher RCGR than plants not previously stressed, making the use of SNR inadequate for these cases. Therefore, the evidence is that SNC should be the percentage stress to use.

As mentioned in Chapter 2, visual symptoms of N deficiency were noticed in the low-N (N0) plants 22 days after plant emergence. For this day, the computed value of SNC was 59.6 %. Seventy four days after plant emergence, SNC reached the season's minimum value of 21.5 %. By harvest time, 122 days after plant emergence the SNC value was 83.8 %. According to Greenwood (1976), in published work with grasses and cereals, the reference point at which N deficiency symptoms begin to develop, the SNC value at 60 %, agrees with the result above. The decrease in SNC with time, 21.5 % at 74 days after emergence, should be expected as the N-stressed plants received the following N applications (Chapter 2): (a) 27 kg N/ha at 30 days after plant emergence;

(b) 54 kg N/ha at 35 days; and, (c) 54 kg N/ha at 65 days. The lowest SNC value, 74 days after emergence, coincided with the maximum CGRs for both N-stressed and non-stressed plants (Figure 28). Also, the maximum N uptake rate (NUPR) occurring around 67 days after emergence, may be an additional factor in bringing the SNC to 21.5 %. After this date differences in growth increased steadily with time (Figure 15, W2N1 vs. W2N0), causing a constant increase in SNC up until harvest, when it reached 84 %. N uptake data indicates that by day 74 the N-stressed plants had taken up almost 60 % of their total 130.9 kg N/ha.

Water Stress

Results of the attempt to apply the concepts discussed by Greenwood (1976), for N stress, to two cases of water stress are presented here. The first case was that of water stress imposed prior to tasseling, where water stress percentage (SWC) was computed based on crop growth rates under the W2N1 versus W3N1 treatment, here designated SWC1. The results, including SWR1 where relative growth rates were used, are presented in Figure 29. Together, the figure depicts the second case of water stress, where the water stress percentage (SWC2) was computed based on crop growth rates under W2N1 vs. W1N1. Results for water stress percentage using relative growth rates (SWR2) are also presented. The absolute and relative growth rates used in both cases are presented in Figure 30 and Figure 31, respectively.

As presented in the crop growth section, the relative crop growth rates (RCGRs) corresponding to the W2N1 and W3N1 treatment combinations did not differ significantly throughout the growing

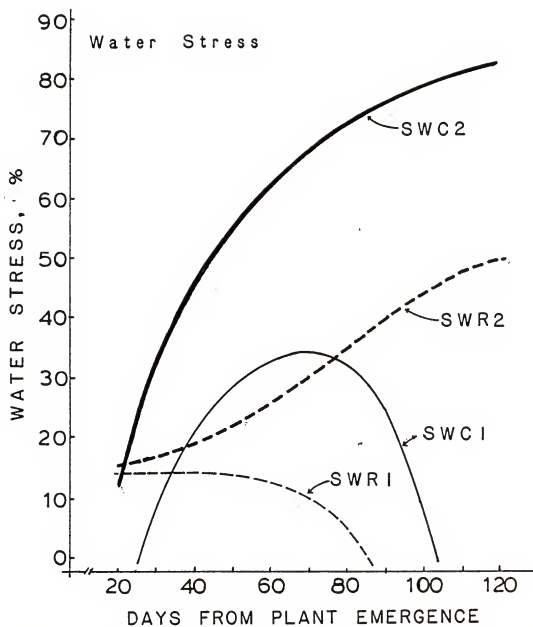


Fig. 29 Corn water stress percentage based on absolute crop growth rates (SWC1 and SWC2), and water stress percentage based on relative crop growth rates (SWR1 and SWR2).

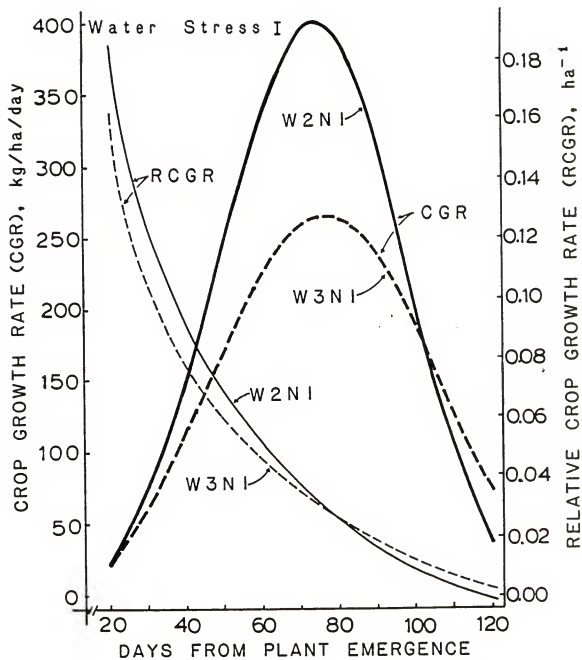


Fig. 30 Growth rates used to compute corn water stress percentage based on absolute crop growth rates (SWC) and water stress percentage based on relative crop growth rates (SWR) of plants under treatments W2N1 and W3N1.

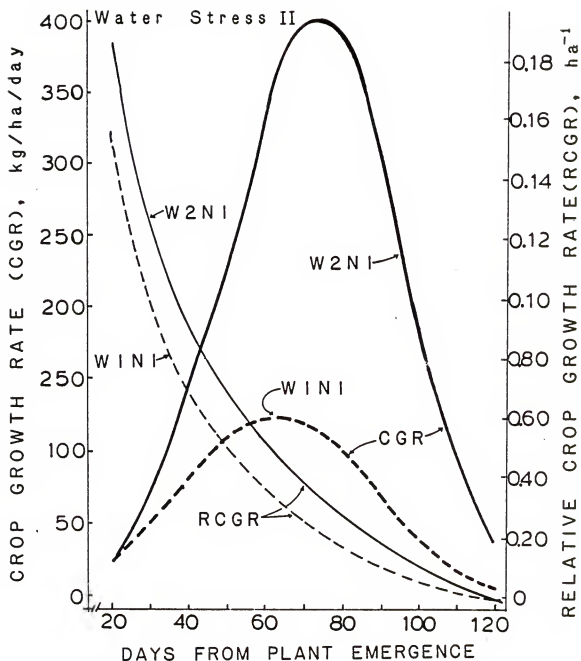


Fig. 31 Growth rates used to compute corn water stress percentage based on absolute crop growth rates (SWC) and water stress percentage based on relative crop growth rates (SWR) of plants under treatments W2N1 and W1N1.

season. Hence, the values of SWR1 (Figure 29) do not indicate a significant effect. For the same reason, the two RCGRs shown in Figure 30, may be visualized as a single curve. For the crop growth rates (CGRs) the significant different effects of W2N1 and W3N1 were noted at 49 days after plant emergence. Due to the number of days between samplings, it could be stated that the differences started at about 43 days after emergence, and was the beginning of the significance of SWC1 (Figure 29). Towards the end of the growing season, corresponding differences did not show at 105 day after plant emergence or until the end of the growing season. Thus, the significance of SWC1 should continue through to about 98 days after plant emergence. The first visual symptoms of wilting prior to tasseling for the water-stressed plants (W3N1) were observed at 56 days after plant emergence. The value of SWC1 at this day was 30.6 %, and reached its maximum of 34 % at 70 days after plant emergence, or 4 days after the prior to tasseling water stress period (Figure 1). At 98 days, after several irrigations and rainfall events, SWC1 dropped to 14.9 %. At the beginning, 43 days after plant emergence, the value of SWC1 was 22.8 %.

In relation to SWR2, despite the significant differences between RCGRs, within 40 and 80 days after plant emergence, did not show enough sensitivity as the CGRs, even under severe water stress. Although to a lesser degree in the case of water stress, they seem to follow the RCGRs tendencies discussed previously.

Crop growth rates (Figure 31) used to compute SWC2, as previously shown, showed a significant difference from the first sampling until 105 days after plant emergence. Thus, the significance of SWC2 (Figure 29) may be considered between 20 days and 110 days after plant emergence. At 20 days after plant emergence the value of SWC2 was 11.7 %. It increased continuously, but at decreasing rates, up to a value of 82.6 % at 110 days after plant emergence. The higher rates of decrease in stress percentage after 70 days can be attributed, in part, to the more uniform rainfall distribution during this period (Figure 1) and the slower decrease in growth rate of rainfed plants. The first visual symptoms of wilt, although slight, were observed 30 days after plant emergence, when the value of SWC2 was 30.3 %, which agrees with the 30.6 % of SWC1.

For the percentage of water stress (SWC), no reference point has been indicated in the literature. The only application of this concept however has been by Power (1971), where only SWR values were reported. The choice between absolute (CGR) and relative (RCGR) rates have not been studied enough to know why relative rate have been preferentially used in stress studies.

Predicted versus Measured N Uptake and Stresses

Cumulative N uptake as predicted by the model NITROSIM (Rao et al., 1981) is compared with that measured in this study.

With exception for responses under severe stress condition, as in treatment W1N0 (Figure 32), there was a good agreement between measured and predicted cumulative N uptake (Figures 33 and 34). It is apparent that by slight adjustment of the

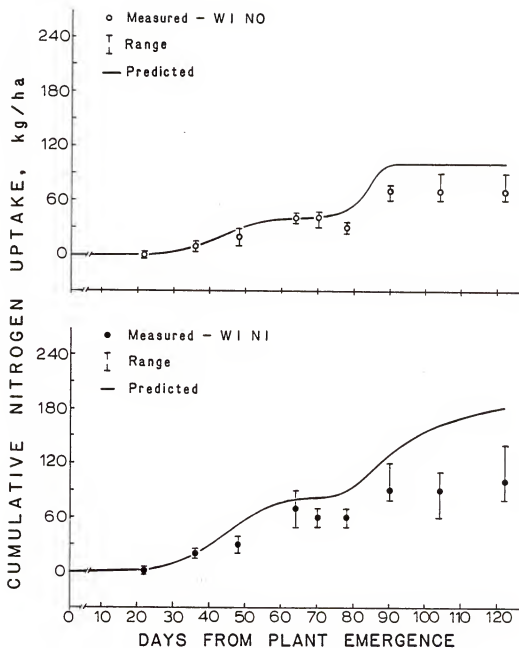


Fig. 32 Measured and predicted (NITROSIM model) cumulative N uptake by corn under two nitrogen levels and rainfed conditions.

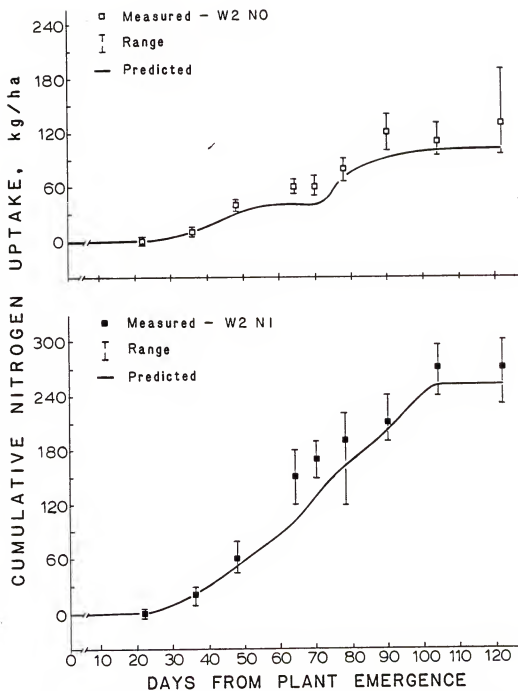


Fig. 33 Measured and predicted (NITROSIM model) cumulative N uptake by corn under two N levels and no water-stress.

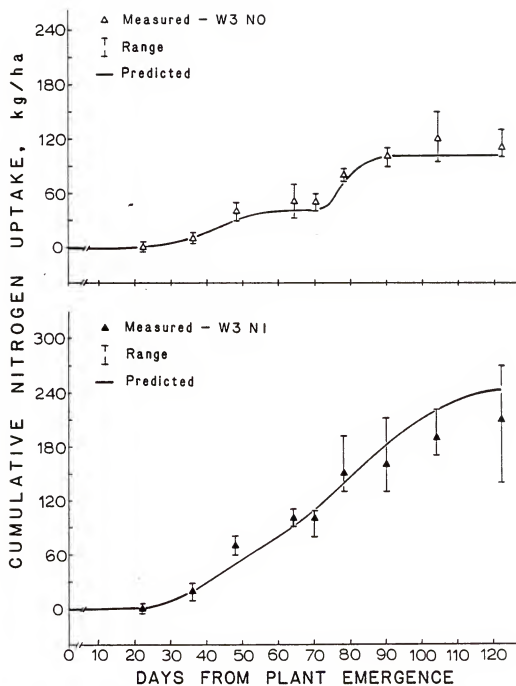


Fig. 34 Measured and predicted (NITROSIM model) cumulative N uptake by corn under two nitrogen levels and water-stress prior to tasseling.

potential cumulative N uptake function of the model, it would produce accurate predictions of N uptake by corn.

Under the most water stressing conditions (W1) or under N-stress (N0) there was a good agreement between the measured and predicted values in indicating a leveling of N uptake between 55 and 75 days after plant emergence, as a consequence of the imposed water and N stresses. Although under conditions of treatment combination W1N1 (Figure 32) there was sufficient available N in soil, the leveling of N uptake seems to have been induced by water stress. Also, in the case of this treatment, the over-prediction of N uptake is due to the fact that the present version of the simulation model does not allow for irreversible and/or cumulative effects of stress on crop growth.

The leveling of the cumulative N uptake, mentioned above, was smoothed in the previous fitting of the cumulative Weibull distribution to the data. Despite this fact, visual symptoms of N and water stresses and the stress percentages at which they occurred were in good agreement within themselves and with data reported in the literature (Greenwood, 1976; Power, 1971).

CHAPTER 5 SUMMARY AND CONCLUSIONS

Analyses of results indicated significant influences of the imposed treatments on the variables measured. Scarcity of similar data in the literature prevented the possibility to relate the results to previous work. Nevertheless, agreement with the limited data reported in the literature and with predictions from the simulation model NITROSIM confirms the adequacy of the data from this study to indicate the effects of water and N stress on corn growth and yield.

Nitrogen, P, and K concentration, as a function of time and plant components, showed significant water and N stress effects. Large percentage differences occurred during late vegetative and early reproductive growth stages. There was a tendency for stressed plants to show higher nutrient concentration than non stressed plants. Rapid decreases in nutrient concentrations occurred during early growth stages for each plant component.

Total uptake of N, P, and K at harvest indicated significant treatment and interaction effects for N uptake. Total nutrient uptake by plants under the optimum treatment (W2N1) showed good agreement with indicated requirements for grain yield. Uptake of N, K, and dry matter accumulation, as a function of time and treatment combination, was adequately described by fitting the

cumulative Weibull distribution function to the data. In the case of P, cumulative uptake could be adequately described by a parabolic equation.

The quantitative measure of N and water stress as % decrease in absolute growth rates was sufficient to indicate the time and level of stress when visual symptoms of deficiency were first noticed. Also, it was sensitive enough to indicate reduction of established stress upon subsequent N or water applications.

Measured cumulative N uptake by corn was in good agreement with simulated N uptake. As expected, there was an over-prediction of N uptake under severe stress as the present version of the simulation model (NITROSIM) does not allow for irreversible and/or cumulative effects of stress on crop growth.

The data generated by this study could be further used in modeling dry matter and major nutrients distribution within corn plants as a function of time and stress.

Further studies of water and nutrient stress effects on corn grown in sandy soils should be performed, where cumulative uptake of nutrients is measured. Experimental treatments should be based on results from simulation models, such as NITROSIM, where supply of water and N are optimized in accordance (or coupling) to plant requirements. Under these conditions, sampling schemes could be optimized in both time and procedure.

Upon the completion of this study, it became evident that it is of decisive importance to consider the coupling of water and N management for crop production on sandy soils. Their relative importance has been demonstrated by sizeable reductions in yield

due to their deficient supply to the plant. On a world-wide scale, the importance of predicting the dynamics of water and N supply and demand cannot be overemphasized as more intensive crop production procedures are adopted on sandy soils, irrespective of technological level.

A P P E N D I X

Table 10. Corn grain yield, and number of seeds per ear as affected by irrigation and N treatments.

Treatment Combination	Replicate	Grain Yield (kg/ha)	Number of Seeds per Ear
W1 NO	1	4063	247
W1 NO	2	4051	246
W1 NO	3	3057	249
W1 NO	4	2695	174
W2 NO	1	7438	362
W2 NO	2	7513	370
W2 NO	3	7118	358
W2 NO	4	6333	281
W3 NO	1	8471	394
W3 NO	2	7832	359
W3 NO	3	6078	352
W3 NO	4	6358	318
W1 N1	1	4065	245
W1 N1	2	3123	216
W1 N1	3	2097	206
W1 N1	4	2800	213
W2 N1	1	11239	496
W2 N1	2	11587	484
W2 N1	3	13482	472
W2 N1	4	12841	530
W3 N1	1	11874	578
W3 N1	2	8261	421
W3 N1	3	9081	382
W3 N1	4	10006	514

Table 11. Treatment Combination W1N0--Average N, P and K content for component parts of corn plants throughout the growing season (Average of four replications).

Days After Emergence	Plant Part	Nutrient		
		N	P	K
		 %		
22	Leaf	4.3	0.7	4.5
	Stem	2.8	0.7	7.8
36	Leaf	2.5	0.6	3.9
	Stem	1.8	0.7	7.6
49	Leaf	2.0	0.3	2.9
	Stem	1.2	0.5	3.9
64	Leaf	1.9	0.3	2.5
	Stem	0.9	0.3	2.4
	Deadleaf	0.6	0.3	2.9
	T+H+S	2.5	0.5	2.3
70	Leaf	1.6	0.3	2.4
	Stem	0.7	0.3	2.6
	Deadleaf	0.7	0.2	2.2
	T+H+S	2.7	0.5	1.7
78	Leaf	1.9	0.3	2.6
	Stem	0.9	0.3	2.6
	Deadleaf	0.7	0.1	1.4
	T+H+S	2.0	0.4	2.0
	Cob	1.1	0.2	0.7
	Grain	1.0	0.2	0.9
91	Leaf	2.4	0.4	1.8
	Stem	0.7	0.3	1.8
	Deadleaf	0.7	0.1	0.9
	T+H+S	1.0	0.3	1.3
	Cob	0.9	0.3	1.0
	Grain	1.9	0.4	0.9
105	Leaf	2.4	0.3	1.7
	Stem	0.7	0.3	2.1
	Deadleaf	0.9	0.1	1.0
	T+H+S	1.0	0.3	1.5
	Cob	0.6	0.2	1.2
	Grain	1.7	0.4	0.6
122	Leaf	1.8	0.4	1.7
	Stem	0.9	0.3	2.1
	Deadleaf	1.3	0.2	0.8
	T+H+S	1.2	0.3	1.2
	Cob	0.9	0.2	1.0
	Grain	1.8	0.5	0.6

Table 12. Treatment Combination W1N1--Average N, P, and K content for component parts of corn plants throughout the growing season (Average of four replications).

Days After Emergence	Plant Part	Nutrient		
		N	P	K
		 %		
22	Leaf	5.0	0.7	4.2
	Stem	4.1	0.8	7.5
36	Leaf	3.4	0.5	3.3
	Stem	2.5	0.6	5.8
49	Leaf	2.2	0.3	2.3
	Stem	1.3	0.3	2.5
64	Leaf	2.3	0.3	2.4
	Stem	0.9	0.2	2.2
	Deadleaf	0.9	0.1	2.5
	T+H+S	2.7	0.5	1.9
70	C + G	1.6	0.3	1.1
	Leaf	2.2	0.3	2.2
	Stem	1.0	0.2	1.7
	Deadleaf	0.9	0.1	1.8
78	T+H+S	2.3	0.4	1.8
	C + G	1.2	0.2	0.6
	Leaf	2.2	0.3	2.4
	Stem	0.9	0.2	1.5
	Deadleaf	0.9	0.1	1.5
	T+H+S	1.5	0.3	1.2
91	Cob	1.8	0.3	1.1
	Grain	3.1	0.5	2.2
	Leaf	2.8	0.4	1.8
	Stem	1.1	0.2	1.7
	Deadleaf	1.0	0.1	0.9
	T+H+S	1.2	0.2	1.2
105	Cob	1.0	0.3	1.0
	Grain	2.1	0.4	0.8
	Leaf	2.2	0.3	1.6
	Stem	0.7	0.1	1.9
	Deadleaf	1.0	0.1	0.7
	T+H+S	1.1	0.2	1.4
122	Cob	0.5	0.1	1.1
	Grain	1.8	0.4	0.5
	Leaf	2.3	0.3	1.6
	Stem	1.1	0.2	2.4
	Deadleaf	1.6	0.2	0.9
	T+H+S	1.1	0.2	1.3
	Cob	0.7	0.1	1.1
	Grain	1.8	0.6	0.7

Table 13. Treatment Combination W2N0--Average N, P, and K content for component parts of corn plants throughout the growing season (Average of four replications).

Days After Emergence	Plant Part	Nutrient		
		N	P	K
		 %		
22	Leaf	5.0	0.7	4.2
	Stem	4.1	0.8	7.5
36	Leaf	3.4	0.5	3.3
	Stem	2.5	0.6	5.8
49	Leaf	2.2	0.3	2.3
	Stem	1.3	0.3	2.5
64	Leaf	2.3	0.3	2.4
	Stem	0.9	0.2	2.2
	Deadleaf	0.9	0.1	2.5
	T+H+S	2.7	0.5	1.9
	C+ G	1.6	0.3	1.1
70	Leaf	2.2	0.3	2.2
	Stem	1.0	0.2	1.7
	Deadleaf	0.9	0.1	1.8
	T+H+S	2.3	0.4	1.8
	C + G	1.2	0.2	0.6
78	Leaf	2.2	0.3	2.4
	Stem	0.9	0.2	1.5
	Deadleaf	0.9	0.1	1.5
	T+H+S	1.5	0.3	1.2
	Cob	1.8	0.3	1.1
	Grain	3.1	0.5	2.2
91	Leaf	2.8	0.4	0.8
	Stem	1.1	0.2	1.7
	Deadleaf	1.0	0.1	0.9
	T+H+S	1.2	0.2	1.2
	Cob	1.0	0.3	1.0
	Grain	2.1	0.4	0.8
105	Leaf	2.2	0.3	1.6
	Stem	0.7	0.1	1.9
	Deadleaf	1.0	0.1	0.7
	T+H+S	1.1	0.2	1.4
	Cob	0.5	0.1	1.1
	Grain	1.8	0.4	0.5
122	Leaf	2.3	0.3	1.6
	Stem	1.1	0.2	2.4
	Deadleaf	1.6	0.2	0.9
	T+H+S	1.1	0.2	1.3
	Cob	0.7	0.1	1.1
	Grain	1.8	0.6	0.7

Table 14. Treatment Combination W2N1--Average N, P, and K content for component parts of corn plants throughout the growing season (Average of four replications).

Days After Emergence	Plant Part	Nutrient		
		N	P	K
		 %		
22	Leaf	5.0	0.6	4.2
	Stem	3.8	0.6	7.3
36	Leaf	3.2	0.5	3.4
	Stem	2.5	0.6	5.8
49	Leaf	3.2	0.4	2.6
	Stem	1.9	0.4	4.1
64	Leaf	3.3	0.3	2.3
	Stem	1.0	0.2	2.0
	T+H+S	2.1	0.4	1.9
	C + G	4.5	0.8	2.7
70	Leaf	3.3	0.3	2.3
	Stem	0.9	0.2	1.7
	T+H+S	1.6	0.3	1.4
	C + G	3.6	0.6	2.2
78	Leaf	2.5	0.3	2.0
	Stem	0.9	0.2	1.4
	Deadleaf	0.0	0.0	0.0
	T+H+S	1.0	0.2	1.0
	Cob	1.3	0.3	1.0
	Grain	4.0	0.6	2.2
91	Leaf	3.0	0.4	2.0
	Stem	0.7	0.2	1.6
	Deadleaf	1.4	0.1	1.3
	T+H+S	0.8	0.2	1.2
	Cob	0.5	0.2	0.7
	Grain	1.7	0.3	0.6
105	Leaf	2.7	0.3	1.9
	Stem	0.5	0.1	1.6
	Deadleaf	1.4	0.1	1.0
	T+H+S	0.6	0.1	1.5
	Cob	0.3	0.1	0.7
	Grain	1.5	0.4	0.5
122	Leaf	2.2	0.3	1.5
	Stem	0.5	0.1	1.8
	Deadleaf	1.5	0.2	1.0
	T+H+S	0.5	0.1	1.1
	Cob	0.4	0.1	0.8

Table 15. Treatment Combination W3N0--Average N, P, and K content for component parts of corn plants throughout the growing season (Average of four replications).

Days After Emergence	Plant Part	Nutrient		
		N	P	K
		 %		
22	Leaf	4.0	0.6	4.7
	Stem	2.5	0.6	8.1
36	Leaf	2.5	0.6	3.9
	Stem	2.0	0.8	7.9
49	Leaf	3.3	0.4	2.8
	Stem	2.2	0.5	6.0
64	Leaf	1.9	0.3	2.5
	Stem	0.8	0.3	2.5
	Deadleaf	0.6	0.2	2.7
	T+H+S	2.8	0.5	2.0
70	Leaf	1.8	0.3	2.3
	Stem	0.5	0.2	1.8
	Deadleaf	0.7	0.1	1.3
	T+H+S	2.2	0.5	1.7
78	C + G	2.5	0.5	1.6
	Leaf	2.4	0.3	2.3
	Stem	0.5	0.2	1.6
	Deadleaf	0.7	0.1	1.0
91	T+H+S	1.1	0.3	1.2
	Cob	1.9	0.4	1.2
	Grain	4.3	0.7	2.3
	Leaf	2.3	0.3	2.1
	Stem	0.5	0.2	1.5
	Deadleaf	0.7	0.1	0.6
	T+H+S	0.8	0.2	1.1
	Cob	0.8	0.2	0.9
105	Grain	1.6	0.3	0.8
	Leaf	2.0	0.3	1.8
	Stem	0.3	0.2	1.7
	Deadleaf	0.7	0.1	0.9
	T+H+S	0.5	0.2	1.5
122	Cob	0.3	0.1	0.9
	Grain	1.2	0.3	0.5
	Leaf	1.8	0.4	1.3
	Stem	0.4	0.2	2.2
	Deadleaf	1.1	0.1	0.8
	T+H+S	0.6	0.1	1.3
	Cob	0.5	0.1	1.0
	Grain	1.2	0.4	0.6

Table 16. Treatment Combination W3N1--Average N, P, and K content for component parts of corn plants throughout the growing season (Average of four replications).

Days After Emergence	Plant Part	Nutrient		
		N	P	K
		 %		
22	Leaf	5.0	0.7	4.2
	Stem	3.7	0.6	7.2
36	Leaf	3.4	0.5	3.2
	Stem	2.6	0.5	5.6
49	Leaf	3.3	0.4	2.3
	Stem	1.9	0.3	3.7
64	Leaf	2.5	0.3	2.3
	Stem	0.9	0.2	1.8
	Deadleaf	0.9	0.1	2.3
	T+H+S	2.4	0.4	1.8
	C + G	1.7	0.3	1.0
70	Leaf	2.7	0.3	2.3
	Stem	0.8	0.2	1.5
	Deadleaf	0.7	0.1	1.4
	T+H+S	1.7	0.3	1.5
	C + G	2.9	0.4	1.8
78	Leaf	3.1	0.3	2.1
	Stem	0.9	0.2	1.4
	Deadleaf	0.6	0.1	1.0
	T+H+S	1.1	0.2	1.1
	Cob	1.4	0.3	1.0
	Grain	4.5	0.7	2.1
91	Leaf	2.9	0.3	1.9
	Stem	0.8	0.2	1.6
	Deadleaf	1.1	0.1	0.7
	T+H+S	0.9	0.2	1.2
	Cob	0.6	0.2	0.8
	Grain	1.7	0.3	0.6
105	Leaf	2.4	0.3	1.9
	Stem	0.8	0.2	1.7
	Deadleaf	1.1	0.1	1.0
	T+H+S	0.6	0.1	1.5
	Cob	0.3	0.1	0.9
	Grain	1.4	0.4	0.5
122	Leaf	1.7	0.3	1.4
	Stem	0.6	0.1	1.9
	Deadleaf	1.5	0.2	1.0
	T+H+S	0.6	0.1	1.1
	Cob	0.5	0.1	0.7
	Grain	1.6	0.5	0.7

Table 17. Treatment Combination W1N0--verage yield of dry matter, and total N, P, and K for component parts of corn plants throughout the growing season (Average of four replications).

Days After Emergence	Plant Part	Dry Matter	Total Uptake		
			N	P	K
			 kg/ha		
22	Leaf	48.4	2.1	0.3	2.2
	Stem	39.1	1.1	0.3	3.1
36	Leaf	215.3	5.3	1.2	8.3
	Stem	125.6	2.2	0.9	9.6
49	Leaf	597.1	12.0	2.0	17.1
	Stem	472.5	5.9	2.2	18.4
64	Leaf	1185.0	22.6	3.3	30.1
	Stem	1603.5	14.6	4.4	39.0
	Deadleaf	118.5	0.7	0.3	3.4
	T+H+S	110.0	2.7	0.6	2.5
70	Leaf	966.2	15.8	2.4	23.5
	Stem	1778.2	12.0	4.6	43.2
	Deadleaf	276.1	2.0	0.5	6.0
	T+H+S	242.7	6.7	1.2	4.2
78	Leaf	578.0	10.5	1.6	15.2
	Stem	1581.2	12.1	3.8	37.1
	Deadleaf	499.6	3.6	0.5	7.2
	T+H+S	196.0	3.3	0.8	3.5
	Cob	56.3	1.2	0.2	0.8
	Grain	16.8	0.5	0.1	0.5
91	Leaf	806.0	19.3	2.8	14.6
	Stem	2126.5	14.3	5.5	37.3
	Deadleaf	476.5	3.1	0.5	4.2
	T+H+S	628.4	6.3	1.6	8.2
	Cob	654.7	5.7	1.7	6.5
	Grain	996.3	19.1	3.5	8.8
105	Leaf	613.2	14.5	2.0	10.6
	Stem	1730.9	13.6	4.8	34.5
	Deadleaf	588.8	5.6	0.9	5.9
	T+H+S	452.0	4.7	1.1	6.9
	Cob	637.9	3.7	1.1	7.7
	Grain	2180.3	32.2	7.8	11.5
122	Leaf	105.2	2.0	0.4	1.8
	Stem	1657.4	15.6	5.1	34.3
	Deadleaf	756.3	9.8	1.4	6.0
	T+H+S	377.3	4.6	0.9	4.5
	Cob	633.6	5.8	1.4	6.7
	Grain	2001.9	31.7	9.7	12.4

Table 18. Treatment Combination W1N1--Average yield of dry matter, and total N, P, and K for component parts of corn plants throughout the growing season (Average of four replications).

Days After Emergence	Plant Part	Dry Matter	Total Uptake		
			N	P	K
..... kg/ha					
22	Leaf	53.1	2.7	0.4	2.2
	Stem	42.7	1.8	0.3	3.2
36	Leaf	360.7	12.1	1.8	11.8
	Stem	265.1	6.6	1.5	15.4
49	Leaf	936.9	20.6	2.7	22.2
	Stem	834.5	10.6	2.4	20.7
64	Leaf	1579.2	36.3	4.0	37.6
	Stem	2453.7	20.9	4.8	54.4
70	Deadleaf	164.1	1.5	0.2	4.0
	T+H+S	260.1	6.6	1.1	4.9
	C + G	6.8	0.2	0.0	0.1
	Leaf	1157.6	24.9	2.8	25.6
	Stem	2733.9	26.6	4.6	46.0
	Deadleaf	384.1	3.5	0.3	6.9
	T+H+S	231.3	4.9	0.9	3.9
78	C + G	68.7	1.6	0.3	0.9
	Leaf	785.5	17.4	2.1	18.8
	Stem	2513.9	22.5	3.5	38.9
	Deadleaf	572.1	5.4	0.4	8.1
	T+H+S	454.3	6.3	1.1	5.3
	Cob	250.0	4.2	0.8	2.7
	Grain	82.2	2.6	0.4	1.9
91	Leaf	875.1	24.0	3.2	15.7
	Stem	2752.6	29.1	5.7	45.3
	Deadleaf	636.3	6.4	0.7	5.6
	T+H+S	660.5	7.8	1.5	7.9
	Cob	675.1	5.7	1.6	6.2
	Grain	1027.7	20.0	3.6	7.9
	105	Leaf	751.3	16.7	2.2
Stem		2626.7	18.7	3.4	47.0
Deadleaf		783.2	7.8	0.8	5.7
T+H+S		448.5	4.6	0.8	6.0
Cob		553.6	2.7	0.6	6.7
Grain		2388.1	41.5	9.2	11.6
122		Leaf	113.0	2.3	0.4
	Stem	2014.2	22.4	4.0	48.2
	Deadleaf	852.1	13.7	1.4	7.8
	T+H+S	497.5	5.3	0.9	6.5
	Cob	594.2	4.4	0.8	6.3
	Grain	3129.5	56.7	17.4	21.5

Table 19. Treatment Combination W2NO--Average yield of dry matter, and total N, P, and K for component parts of corn plants throughout the growing season (Average of four replications).

Days After Emergence	Plant Part	Dry Matter	Total Uptake		
			N	P	K
..... kg/ha					
22	Leaf	60.2	2.5	0.4	2.8
	Stem	45.6	1.2	0.3	3.6
36	Leaf	229.4	5.6	1.2	8.8
	Stem	118.6	2.3	0.9	8.6
49	Leaf	855.1	25.5	3.5	22.5
	Stem	684.1	12.9	3.5	35.7
64	Leaf	1776.6	33.7	4.9	41.0
	Stem	3473.5	18.9	9.7	77.8
	Deadleaf	117.0	0.8	0.3	2.7
	T+H+S	258.7	5.9	1.3	4.9
70	C + G	9.4	0.3	0.1	0.2
	Leaf	1569.3	26.8	3.4	34.2
	Stem	5017.8	21.7	11.5	81.4
	Deadleaf	271.0	1.6	0.4	3.9
	T+H+S	468.4	7.5	1.7	6.6
	C + G	78.3	2.0	0.4	1.5
78	Leaf	1495.2	33.5	4.2	31.8
	Stem	4975.9	24.4	10.4	65.7
	Deadleaf	269.3	1.6	0.2	2.9
	T+H+S	1113.5	12.0	2.9	12.6
	Cob	346.2	7.6	1.4	5.2
	Grain	94.0	3.7	0.6	2.5
91	Leaf	1736.1	40.6	5.7	33.8
	Stem	5568.5	21.1	12.5	73.5
	Deadleaf	289.0	1.9	0.3	1.8
	T+H+S	1503.4	10.4	3.1	15.6
	Cob	1332.8	8.6	2.5	10.2
	Grain	2452.7	36.2	7.8	17.3
105	Leaf	1384.2	22.8	3.6	24.5
	Stem	4936.5	11.2	11.4	65.6
	Deadleaf	667.3	3.8	0.6	5.7
	T+H+S	1244.7	5.4	1.7	15.6
	Cob	1902.5	6.1	1.5	13.9
	Grain	5220.0	63.6	16.8	24.0
122	Leaf	430.2	6.7	1.9	5.1
	Stem	4062.5	12.0	14.0	67.2
	Deadleaf	1049.0	9.4	1.7	8.8
	T+H+S	952.8	4.3	1.3	9.8
	Cob	1234.3	6.1	1.1	8.5
	Grain	6851.8	92.4	32.0	41.7

Table 20. Treatment Combination W2N1--Average yield of dry matter, and total N, P, and K for component parts of corn plants throughout the growing season (Average of four replications).

Days After Emergence	Plant Part	Dry Matter	Total Uptake		
			N	P	K
..... kg/ha					
22	Leaf	52.2	2.6	0.3	2.2
	Stem	41.4	1.6	0.3	3.0
36	Leaf	380.6	12.3	1.9	12.8
	Stem	270.2	6.7	1.5	15.5
49	Leaf	1291.8	41.5	5.1	33.0
	Stem	1171.7	21.9	4.6	47.5
64	Leaf	2461.2	81.2	7.9	56.3
	Stem	4952.0	50.5	9.8	96.6
70	T+H+S	830.4	17.5	3.1	15.9
	C + G	55.7	2.3	0.4	1.4
	Leaf	2432.0	79.6	7.5	55.5
	Stem	6741.2	59.8	11.9	110.5
	T+H+S	1339.5	20.9	3.7	19.2
78	C + G	239.9	8.3	1.4	5.2
	Leaf	2508.1	64.0	8.3	50.4
	Stem	6907.3	64.2	13.1	98.5
	Deadleaf	0.0	0.0	0.0	0.0
	T+H+S	2262.9	21.3	4.4	22.9
91	Cob	1481.9	19.1	3.9	14.3
	Grain	530.8	19.5	2.7	10.1
	Leaf	2107.8	64.0	7.9	41.2
	Stem	5616.0	41.8	9.5	87.6
	Deadleaf	259.8	3.6	0.3	3.4
105	T+H+S	1666.0	13.0	2.9	19.5
	Cob	1572.0	7.9	2.5	11.5
	Grain	4859.3	80.4	15.4	28.8
	Leaf	2014.3	55.3	6.1	37.6
	Stem	5460.2	29.7	6.1	89.3
122	Deadleaf	658.5	9.5	0.7	6.9
	T+H+S	1682.2	9.8	1.7	24.7
	Cob	2163.9	7.5	1.4	15.9
	Grain	10407.8	155.4	38.6	51.8
	Leaf	565.7	12.3	1.5	8.2
122	Stem	4947.2	26.4	4.8	91.7
	Deadleaf	1412.0	21.2	2.1	14.6
	T+H+S	1449.9	7.4	1.2	16.0
	Cob	1745.1	7.5	0.8	14.2
	Grain	11880.6	192.9	61.8	76.7

Table 21. Treatment Combination W3N0--Average yield of dry matter, and total N, P, and K for component parts of corn plants throughout the growing season (Average of four replications).

Days After Emergence	Plant Part	Dry Matter	Total Uptake		
			N	P	K
..... kg/ha					
22	Leaf	45.1	1.8	0.3	2.1
	Stem	36.0	0.9	0.2	2.9
36	Leaf	197.0	4.8	1.1	7.7
	Stem	109.4	2.1	0.8	8.6
49	Leaf	754.9	25.3	3.1	21.3
	Stem	526.1	11.4	2.8	32.4
64	Leaf	1460.0	27.6	4.1	37.0
	Stem	2258.2	17.2	6.2	54.6
70	Deadleaf	197.0	1.3	0.3	5.2
	T+H+S	161.4	4.5	0.9	3.2
	Leaf	1506.1	26.4	3.8	35.0
	Stem	3426.7	16.7	6.9	61.9
	Deadleaf	317.9	2.1	0.3	4.1
	T+H+S	390.7	8.5	1.7	6.5
	C + G	35.4	1.2	0.2	0.7
78	Leaf	1399.6	33.2	4.1	31.7
	Stem	3751.8	19.6	7.1	58.5
	Deadleaf	274.0	1.9	0.2	2.9
	T+H+S	908.3	10.0	2.4	10.7
	Cob	439.2	8.0	1.6	5.3
91	Grain	96.4	4.2	0.6	2.3
	Leaf	1551.2	36.2	5.0	32.1
	Stem	4027.6	18.2	8.1	61.5
	Deadleaf	353.0	2.4	0.3	2.0
	T+H+S	1168.0	9.7	2.6	13.0
105	Cob	1085.3	8.2	2.6	10.2
	Grain	1679.4	26.2	5.2	13.0
	Leaf	1276.8	25.5	3.6	22.6
	Stem	3763.2	11.4	6.9	62.9
	Deadleaf	747.6	5.5	0.6	6.6
	T+H+S	1049.1	5.7	1.7	15.8
	Cob	1371.6	4.6	1.3	13.1
122	Grain	5688.2	66.8	18.6	28.7
	Leaf	151.1	2.7	0.5	2.1
	Stem	2601.9	9.5	4.6	58.1
	Deadleaf	1161.0	13.1	1.6	9.3
	T+H+S	728.1	4.5	0.8	9.7
	Cob	1023.3	5.2	0.7	10.4
	Grain	6374.9	78.4	27.5	39.3

Table 22. Treatment Combination W3N1--Average yield of dry matter, and total N, P, and K for component parts of corn plants throughout the growing season (Average of four replications).

Days After Emergence	Plant Part	Dry Matter	Total Uptake		
			N	P	K
			 kg/ha		
22	Leaf	57.2	2.9	0.4	2.4
	Stem	46.5	1.7	0.3	3.4
36	Leaf	355.8	12.0	1.6	11.4
	Stem	255.2	6.6	1.4	14.1
49	Leaf	1369.4	45.7	5.0	30.9
	Stem	1206.7	22.6	3.9	44.6
64	Leaf	2115.1	53.1	5.8	49.8
	Stem	3922.5	33.4	6.8	69.3
70	Deadleaf	166.0	1.5	0.1	3.8
	T+H+S	411.6	9.6	1.8	7.3
	C + G	13.5	0.4	0.1	0.3
	Leaf	1631.0	43.8	4.4	37.4
	Stem	4198.9	33.6	6.8	60.7
	Deadleaf	276.4	1.7	0.2	3.6
	T+H+S	766.2	12.5	2.3	11.7
78	C + G	190.7	5.4	0.8	3.4
	Leaf	1996.0	62.5	6.7	41.6
	Stem	4621.6	38.7	8.0	62.3
	Deadleaf	231.6	1.4	0.2	2.3
	T+H+S	1678.8	18.8	3.9	18.5
	Cob	1116.4	15.6	3.1	11.4
	Grain	277.2	12.5	1.8	6.1
91	Leaf	1629.0	46.9	5.5	30.8
	Stem	4056.8	31.0	6.5	67.2
	Deadleaf	344.2	4.1	0.4	2.5
	T+H+S	1147.0	9.9	2.0	13.8
	Cob	1210.9	7.0	2.0	10.0
	Grain	3441.3	58.1	11.4	22.0
	105	Leaf	1447.6	34.8	4.5
Stem		3384.9	26.2	5.3	58.1
Deadleaf		782.2	8.7	0.8	8.0
T+H+S		1054.5	6.1	1.1	15.7
Cob		1418.5	4.8	0.8	12.6
Grain		7983.0	112.8	28.7	36.3
122		Leaf	199.4	3.4	0.5
	Stem	3653.1	21.5	4.5	70.6
	Deadleaf	1360.2	20.6	2.0	13.0
	T+H+S	1102.2	6.6	1.1	12.4
	Cob	1551.5	8.1	1.2	10.8
	Grain	9344.3	151.4	48.3	61.4

Table 23. Crop growth, N uptake, P uptake, and K uptake rates of corn as affected by irrigation and N treatments (Average of four replications).

Days from Emergence	Rate	Treatment Combination					
		W1N0	W2N0	W3N0	W1N1	W2N1	W3N1
		 kg/ha/day					
22	Growth	11.7	13.1	7.9	25.2	30.9	30.0
	N Uptake	0.3	0.4	0.3	0.6	1.0	0.9
	P Uptake	0.1	0.2	0.1	0.1	0.2	0.1
	K Uptake	0.3	0.5	0.5	0.5	0.7	0.9
36	Growth	37.9	61.8	41.6	65.6	111.1	94.0
	N Uptake	0.6	1.0	0.9	1.1	2.4	1.9
	P Uptake	0.1	0.2	0.2	0.1	0.3	0.2
	K Uptake	1.4	2.1	1.7	1.9	2.8	2.5
49	Growth	73.1	152.6	111.9	106.5	231.0	180.6
	N Uptake	0.9	1.6	1.5	1.4	3.8	2.7
	P Uptake	0.2	0.3	0.3	0.2	0.5	0.3
	K Uptake	2.6	4.1	3.4	2.8	5.9	3.6
64	Growth	104.9	274.7	222.6	127.3	364.4	166.4
	N Uptake	1.1	2.0	1.9	1.4	4.4	3.0
	P Uptake	0.2	0.4	0.3	0.2	0.6	0.5
	K Uptake	0.8	2.6	2.2	0.9	3.7	2.5
70	Growth	107.7	302.5	256.2	122.4	390.9	279.4
	N Uptake	1.1	2.0	2.0	1.3	4.2	2.9
	P Uptake	0.2	0.5	0.4	0.2	0.7	0.5
	K Uptake	0.3	1.5	1.7	0.4	2.4	1.7
78	Growth	99.8	199.4	169.7	105.4	387.1	269.6
	N Uptake	1.0	1.8	1.8	1.1	3.7	2.5
	P Uptake	0.2	0.5	0.4	0.3	0.8	0.6
	K Uptake	0.1	0.8	1.2	0.2	1.4	1.0
91	Growth	67.1	202.8	197.1	65.6	295.2	200.1
	N Uptake	0.8	1.3	1.3	0.9	2.4	1.8
	P Uptake	0.2	0.6	0.5	0.3	0.9	0.7
	K Uptake	0.0	0.3	0.4	0.1	0.6	0.4
105	Growth	31.8	79.1	70.8	29.2	157.5	111.8
	N Uptake	0.5	0.9	0.6	0.6	1.1	1.1
	P Uptake	0.3	0.8	0.5	0.3	1.1	0.9
	K Uptake	0.0	0.1	0.1	0.0	0.3	0.1
122	Growth	10.2	13.3	6.5	8.0	46.5	50.7
	N Uptake	0.3	0.6	0.2	0.4	0.3	0.7
	P Uptake	0.3	0.9	0.6	0.4	1.2	1.1
	K Uptake	0.0	0.0	0.0	0.0	0.1	0.0

Table 24. Relative rates of crop growth, N uptake, P uptake, and K uptake of corn as affected by irrigation and N treatments (Average of four replications).

Days from Emergence	Rate	Treatment Combination					
		W1N0	W2N0	W3N0	W1N1	W2N1	W3N1
		 day ⁻¹					
22	Growth	0.16	0.19	0.20	0.15	0.17	0.16
	N Uptake	0.13	0.14	0.15	0.11	0.14	0.12
	P Uptake	0.07	0.09	0.09	0.08	0.09	0.10
	K Uptake	0.21	0.20	0.19	0.19	0.20	0.16
36	Growth	0.10	0.12	0.12	0.09	0.10	0.10
	N Uptake	0.08	0.08	0.09	0.07	0.08	0.07
	P Uptake	0.04	0.06	0.05	0.05	0.06	0.06
	K Uptake	0.12	0.11	0.11	0.10	0.12	0.09
49	Growth	0.07	0.08	0.09	0.06	0.07	0.07
	N Uptake	0.05	0.05	0.06	0.04	0.05	0.05
	P Uptake	0.03	0.04	0.04	0.04	0.04	0.05
	K Uptake	0.06	0.07	0.07	0.05	0.07	0.05
64	Growth	0.04	0.05	0.06	0.03	0.05	0.04
	N Uptake	0.03	0.03	0.04	0.03	0.03	0.03
	P Uptake	0.03	0.03	0.03	0.03	0.03	0.03
	K Uptake	0.01	0.02	0.02	0.01	0.02	0.02
70	Growth	0.03	0.04	0.05	0.03	0.04	0.04
	N Uptake	0.03	0.03	0.03	0.02	0.03	0.02
	P Uptake	0.02	0.03	0.03	0.02	0.03	0.03
	K Uptake	0.01	0.01	0.02	0.01	0.01	0.01
78	Growth	0.03	0.03	0.04	0.02	0.03	0.03
	N Uptake	0.02	0.02	0.02	0.02	0.02	0.02
	P Uptake	0.02	0.03	0.02	0.02	0.03	0.03
	K Uptake	0.00	0.01	0.01	0.00	0.01	0.01
91	Growth	0.01	0.02	0.02	0.01	0.02	0.02
	N Uptake	0.01	0.01	0.01	0.01	0.01	0.01
	P Uptake	0.02	0.02	0.02	0.02	0.02	0.02
	K Uptake	0.00	0.00	0.00	0.00	0.00	0.00
105	Growth	0.01	0.01	0.01	0.00	0.01	0.01
	N Uptake	0.01	0.01	0.01	0.01	0.00	0.01
	P Uptake	0.02	0.02	0.02	0.02	0.02	0.02
	K Uptake	0.00	0.00	0.00	0.00	0.00	0.00
122	Growth	0.00	0.00	0.00	0.00	0.00	0.00
	N Uptake	0.00	0.00	0.00	0.00	0.00	0.00
	P Uptake	0.01	0.02	0.02	0.01	0.02	0.02
	K Uptake	0.00	0.00	0.00	0.00	0.00	0.00

Table 25. Data sets and input values of each parameter within its respective data set as documented in the NITROSIM model. +

Data Set	Parameters' Values
1	30 / 123 / 1 / 1 / 67 / 0.2;
2	4 / 2.5 / 4.5 / 10 / 10 / 0 / 10 / 0;
3	150 / 0.342 / 0.0042 / 0.00002 / 0.00003 / 0.00033 / 0.00005 / 0.0001;
4	55; ‡
	...; §
5	6; ‡
	...; §
6	0;
7	8; 75 / 0.022 / 90 / 0.022 / 105 / 0.025 / 120 / 0.025;
8	5; 10 / 0.10 / 25 / 0.09 / 60 / 0.075 / 90 / 0.12 / 105 / 0.25;
9	2; 10 / 0.25 / 120 / 0.30;
10	2; 0 / 0.20 / 120 / 0.25;
11	1; 40 / 0.20;
12	1; 30 / 1.55;
13	2; 15 / 2.5 / 30 / 0.5;
14	2; 15 / 5.0 / 30 / 1.5;
15	2; 5 / 15000 / 30 / 9000;
16	0.5 / 0.5 / 0.5 / 0.5 / 0.003;

+ Jessup, personal communication.

‡ Maximum number of events.

§ Too numerous to be given or given in the text.

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BIOGRAPHICAL SKETCH

Luiz Severo Mugica Mutti was born on 19th June 1942 in Uruguaiana, State of Rio Grande do Sul (RS), Brazil. For 19 years, he lived in the same town, which belongs to a county bordered by Argentina and Uruguay.

In 1965 he received his B.S. degree of Engenheiro-Agronomo. After two years, he received the degree of Master of Science in soil survey from the Ghent State University, Ghent, Belgium.

Since 1968, he has participated in several county and state-wide soil surveys in Southern Brazil and taught soil science at the undergraduate level in the Federal University of Santa Maria, Santa Maria, RS, Brazil. Before coming to the University of Florida, he spent 4 years in reduced-tillage systems research for wheat-soybean crop sequence.

In September 1979, he entered the University of Florida, in a graduate training program with emphasis in soil physics. Upon graduation, he will return to Brazil to continue his teaching and research duties at the Soils Department, Center for Rural Sciences, Federal University of Santa Maria, Santa Maria, RS, Brazil.

He is married to artist Jeanine, who gave him two lovely daughters, Adriane and Luciane.

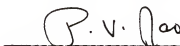
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J. M. Davidson, Chairman
Professor of Soil Science

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P. S. C. Rao, Cochairman
Associate Professor of
Soil Science

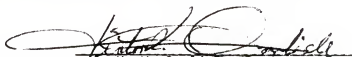
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P. V. Rao
Professor of Statistics

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.


L. C. Hammond
Professor of Soil Science

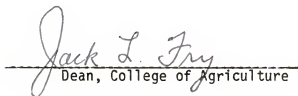
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A handwritten signature in dark ink, appearing to read 'V. W. Carlisle', written over a horizontal line.

V. W. Carlisle
Professor of Soil Science

This dissertation was submitted to the Graduate Faculty of the College of Agriculture and to the Graduate School, and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

April 1984

A handwritten signature in dark ink, appearing to read 'Jack L. Fry', written over a horizontal line.

Dean, College of Agriculture

Dean for Graduate Studies
and Research